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REVIEW

Future opportunities for products derived from black soldier fly (BSF) treatment as animal feed and fertilizer - A systematic review

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Abstract

The pursuit of novel food products with good nutritional value for both direct and indirect human consumption is crucial. Given the nutritional benefits of insects and the sustainability of this sort of farming, using them as food for farmed animals is a promising alternative. In this regard, the black soldier fly (*Hermetia illucens*) is most capable of efficiently converting a wide variety of organic materials, from food waste to manure, into insect biomass generating value and closing nutrient loops as they reduce pollution and costs. Their larvae have 29% fat and 42% crude protein, yet they have more saturated fats than most insects. They don't concentrate hazards such as mycotoxins or insecticides. Although rapid development is expected, insects remain underutilized in the animal feed industry mainly due to technical, financial, and regulatory barriers. The social stigmas and legal prohibitions against eating organisms that eat waste are added to extant taboos facing insect consumption. Bridging the knowledge gap is crucial to bring together stakeholders and to better understand the opportunities and challenges of this novel industry, so as to develop guidelines on producing insects on an industrial scale to facilitate the wider use of BSF products as animal feed, and fertilizer.

Keywords Black soldier fly · Fertilizer · Animal feed · Opportunities · Challenges · Fish · Poultry

1 Introduction

According to research, the world's population will increase to roughly 9.6 billion people by 2050. Hence, to feed the population in 2050, the Food & Agricultural Organization (FAO) predicts food production will need to rise by 70%, with double meat production in beef, poultry, and hog (Higa et al., 2021). Therefore, the demand for meat and seafood is speculated to rise with the rising of aquaculture business. Food manufacturers have been compelled to develop novel alternative protein-based products to muscle meat in response to consumer demand for sustainable food. The production of muscle meat

Extended author information available on the last page of the article from livestock animals contributes to the deterioration of the ecosystem worldwide by consuming land (30%) and its water (8%) in addition to the gas emissions (14.5%) (over those from transportation) (Lamb et al., 2021; Siddiqui et al., 2022). Eutrophication and deforestation, which account for greenhouse gas (GHG) emissions (34%), are further growing problems brought on by cattle production (Siddiqui et al., 2022).

In several nations throughout the world, insects have recently been recognized as a significant potential source of sustainable raw materials for animal feeds. In terms of nutritional make-up, amino acid profile, and feed acceptance—as a component of various animal species' natural diets—insects satisfy the dietary needs of animals (Schiavone et al., 2018). The mass production of insect-based proteins could be a promising alternative to animal meat. Insect-based protein production requires less land, emits low GHGs, has low feed-food compatibility, and has the ability to transform organic wastes into valuable proteins, making the insects good for the environment (van Huis & Oonincx, 2017). For instance, using insects to bioconvert waste materials is an innovative strategy and a striking illustration of a circular economy that is sustainable (Sogari et al., 2019).

Given their nutritional value, minimal space demand, and high acceptance by various animals, including fish, poultry, and reptiles who consume insects in their natural habitat, insects have a lot of promise as feed (Makkar, 2018). Furthermore, it is ethically acceptable to produce insects used as feed on organic wastes like fish offal and dung (Oteri et al., 2022). High nutritional qualities, feed efficiency, and reproductive capabilities are advantages of employing insects as cattle feed (Van Huis & Gasco, 2023). Insects can provide by-products, are naturally found in the diets of some livestock (such as fish, poultry, and pigs), and can have additional socioeconomic and environmental advantages (Devi & Kim, 2014). There are many types of insects that are acceptable, including mealworms, grasshoppers, crickets, locust, house fly larvae, silkworms, and black soldier fly (BSF) and its larvae (BSFL) (Sogari et al., 2019).

BSFL, *Hermetia illucens* L. (Diptera: Stratiomyidae), is thought to have the most potential for use as feed. Insect production depends on the environment, but generally speaking, they use less area and emit significantly less water and GHG than conventional feed (Rehman et al., 2023). Assuring a certain level of safety is a crucial component in commercializing any product. A major concern with using insects as food is standardization, because different insects are reared on different substrates, and different insect-consuming nations consequently have different legal systems (Riera, 2018). Laws governing the safety of the substrate that insects are raised on, for example, may not be as stringent in some areas as they are in the European Union (EU). According to experts, the primary obstacle preventing the sector from taking off globally is the stringent EU rules (Van Huis & Gasco, 2023). The poorest and most vulnerable people in society can gain from insect rearing. Insects will eventually replace traditional feed as a more affordable and environmentally friendly source of protein with significant technological advancements. Insects raised on waste have the potential to reduce and value global waste sources (Heuel et al., 2021). By making investments in renewable energy, insect farming will become less dependent on fossil fuels (Surendra et al., 2016).

The BSF market has a limited economic potential now, but it is anticipated to rise rapidly over the next few years. The global market had a 2019 value of $128 million but is expected to increase to $3.4 billion by 2030 (Foo & Li, 2021). In addition, Asia Pacific held the greatest share of the global market in 2019 in terms of volume (57.1%) and value (almost 50%). The demand for meat and seafood is expected to rise along with the global population, and the aquaculture business is expanding as well (Foo & Li, 2021).

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In the past ten years, BSFL treatment has emerged as a viable way of treating biodegradable garbage that may contribute to the three difficulties listed. Biodegradable waste is transformed into two products in this insect-based treatment: a larval biomass rich in proteins and lipids that may be utilized in animal feed and a processing residue known as frass that can be used as fertilizer in a variety of ways (Kumar et al., 2018). This method adheres to the concepts of a circular bio economy, in which the waste from one process becomes the resource in another because two valuable goods are produced (van der Fels-Klerx et al., 2020). One of the key outcomes of the process was frass, which may take the place of traditional N fertilizers and reduce the risk of global warming that comes with using any type of conventional N fertilizer (Schmitt & de Vries, 2020). Reports indicate that the process for frass production from BSFL shows less environmental damage, minimal utilization of energy and water, and less impact on global warming and other impact categories than the process of organic fertilizer (Lopes et al., 2022). It is interesting to note that the environmental advantages of producing insect frass are strongly tied to the substrate source used to feed the larvae, with lesser impacts being documented when using non-utilized waste streams instead of conventional items like soybean meal (Heuel et al., 2021). Frass has begun to draw attention in recent years due to its ongoing production in waste treatment facilities, plenty of plant nutrients, and potential to help the agribusiness industry generate cash (Lugato et al., 2020). However, compared to the larval biomass obtained through the same method, frass has not received as much attention. Particularly, there are several information gaps about the application of frass and its advantages in farming and other cultivation-related activities (Lopes et al., 2022).

BSFL composting, using organic wastes to produce frass, and also using BSF as animal feed have all been the subject of extensive investigation. This study will provide the reader with an extensive and succinct source of knowledge by summarizing the results of selected prior studies on BSFL organic waste treatment and the potential use of BSF by-products that focused on larvae and frass.

2 Methodology

2.1 Eligibility criteria, articles search strategy and dataset development

We applied the following inclusion in this review by following population, intervention, comparators, outcomes, and study design (PICOS) as follows: (1) Consumers; (2) BSF products; (3) consumer studies focused on future opportunities for products derived from the black soldier fly treatment as animal feed and fertilizer; (4) articles consistently written in English and published after being peer reviewed. After careful evaluation, a raw dataset that reported consumer studies focused on future opportunities for products derived from the black soldier fly treatment as animal feed and fertilizer was constructed and extracted. The articles were carefully chosen and selected following the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines (Moher et al., 2009). Published articles were extracted into Mendeley references manager (https://www.mendeley.com/) with the following criteria: (1) name of the author; (2) publication year; (3) year of study; (4) type of BSF product derived and evaluated; and (5) results obtained.

Initially, 1050 results were achieved through the Science Direct database (https://www.sciencedirect.com/). From these, 200 articles were excluded due to not being related to our topic, future opportunities for products derived from the BSF treatment

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as animal feed and fertilizer and 185 articles for being duplicates; 435 articles were excluded as they did not discuss the effects of different BSF products derived and 15 articles for the language (non-English); 37 articles were excluded for non-peer reviewed papers/ inappropriate interpretation of results/ non-availability of full texts; finally, 178 articles remained for systematic review for consumer studies focused on future opportunities for products derived from the black soldier fly treatment as animal feed and fertilizer (Fig. 1). The algorithm search key for the published article was set from 2012 to 2022, using the terms ("Black soldier fly") AND ("BSF products") AND ("animal feed" OR "fertilizer" OR "Life Cycle Assessment" OR "opportunities and challenges").

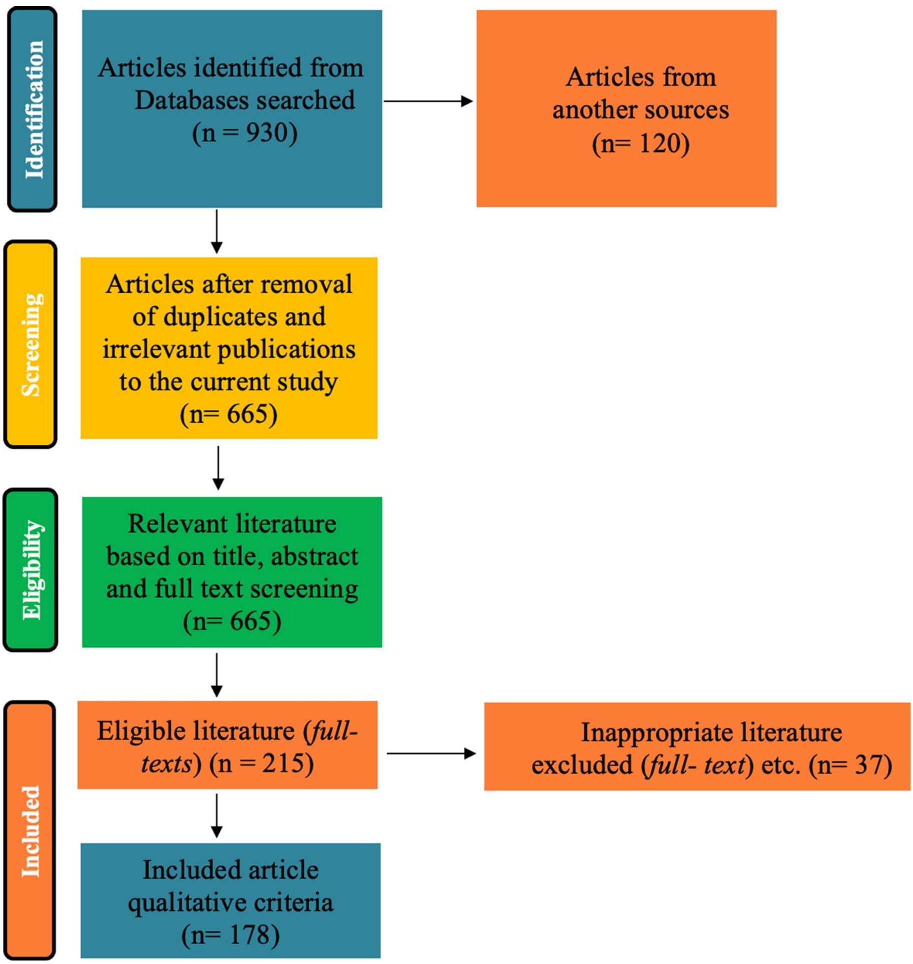

Fig. 1 Diagram flow of article selection

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3 Products derived from black soldier fly treatment

3.1 Animal feed

Animal feed is a food item that is consumed by the domestic animals in the course of Animal Husbandry. Animal feed is the most important source of nutrition intake by animals that ensures improved immunity, accelerated growth, and good health. With an increasing initiative for the production of sustainable protein animal feed acts as a high-value protein source for both livestock and fish. The commercial livestock farming success hugely depends on the constant best quality nutritious feeds supply. The livestock and the animal feed market are in harmony with each other in growth. The animal feed market is expected to surge in the coming years with furiously growing per capita consumption of eggs, boiler meat, and milk (Henchion et al., 2021). By 2050, the FAO of the United Nations predicts that 70% more food must be produced globally (van Dijk et al., 2021). Global meat output per person is expected to rise by 0.3% P.A. to 35.4 kg in retail weight equivalent by 2030, according to the OECD-FAO Agricultural Outlook 2021–2030 (OECD/FAO, 2021). As per the International Feed Industry Federation (IFIF), the manufacture of meat (poultry, swine, and cattle) will even double in the nearby future (Veldkamp & Bosch, 2015). The majority of the increase in meat production is, overall, attributed to developing regions, which will produce 80% more than they do now (https://www.investmentmonitor.ai). Additionally, it was noted that during the following ten years, beef consumption is expected to rise to 76 Mt, accounting for almost 16% of the overall growth in meat consumption over the baseline period (OECD/FAO, 2021). Additionally, it is anticipated that during the next ten years, the global consumption of pig meat would rise to 127 Mt, making up 28% of the overall growth in meat consumption (OECD/FAO, 2021). As a effect, it is anticipated that the market for animal feed will be driven by an increase in meat consumption followed by population growth.

Currently, fish meal, processed animal proteins, and soybean meal are significant protein constituents for animal feed (Veldkamp et al., 2012). However, the usage of processed animal proteins in animal feed is outlawed in the European Union as a result of TSE laws (Fumière et al., 2009). The quantity of land that can be utilised for soya farming is also constrained globally, while overfishing in the ocean has decreased the population of small pelagic forage fish, which are needed to produce fish meal and fish oil (Veldkamp et al., 2012). In the previous five years, prices have risen due to the increasing scarcity of resources needed to create these more in-demand ingredients, which already account for 60–70% of production expenses (Veldkamp et al., 2012). Alternative (animal) protein sources are thus desperately needed for aquaculture and cattle (Veldkamp et al., 2012). Insects are an alternate source of animal protein that can be sustainably farmed on organic side streams. Many factors contribute to their high feed conversion efficiency, but their cold blood is most certainly one of them. On a dry matter basis, insects have a protein content of 30–70% (Veldkamp et al., 2012). When a drought or other extreme weather event brought on by climate change affects farmers or herders, they frequently have to switch to more expensive manufactured animal feed, which can have a negative impact on their capacity to make a living (Gitz et al., 2016).

Today insect protein is used in fish feed and pet food. A brief overview of feed resources used to prepare different animal feeds and major nutritional composition (Table 2) for poultry, livestock, fish, and pets is depicted in Table 1. The next step will be to authorize the use of insect protein for poultry feed and other livestock. Many articles deal with using

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Table 1 Overview of insect-based feed resources for poultry, livestock, fish, and pet

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL Meal	NA	Killing, drying, and defatting method	larvae meal can partially replace conventional soya bean meal and soya bean oil in the diet for growing broiler quails, thus confirming to be a promising insect protein source for the feed industry	Broiler quails (*Coturnix coturnix japonicaI*)	Cullere et al. (2018)
Defatted BSFL meal and fat	Wheat bran (air dry) & solubles from wheat distillery	Larvae were killed by heat shock, dried, and mechanically defatted with an industrial press	The results indicate that soybean-based feeds can be replaced completely by black soldier fly meal and fat in diets of high-performing layers	Lohmann Brown Classic hens (Crossbreed)	Heuel et al. (2021)
BSF prepupae meal	Organic kitchen waste, fruits and vegetables	After harvest, the BSF pre-pupae were dried at 65 °C and ground to a meal	BSF pre-pupae meal (up to 15%) can be included in broiler diets without influencing the carcass, sensory or meat quality characteristics	Cobb broiler chicks (*Gallus gallus domesticus)*	Pieterse et al. (2019)
BSF Prepupae meal	Vegetable and fruit wastes	Harvested prepupae processed, sun dried (32 °C) for three days and finally, oven dried for three days at 50 °C. The ground (around 500 µm) prepupae was used for the broiler feeding trials	Black soldier fly prepupae meal can be incorporated at 5% in broiler diet	Cobb chicks (*Gallus gallus domesticus)*	Elangovan et al. (2021)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
Black soldier fly larvae oil (BSO)	NA	Obtained from company	Findings suggest that BSO can replace Soybean Oil (SO) in the formulation of broiler diets, with 50% BSO being the best	Kebao broiler chicks (*Gallus gallus domesticus)*	Chen et al. (2022)
Live Black soldier fly larvae	NA	Larvae were produced in GMP + and Secure-Feed certified facility under HACCP (Hazard Analysis Critical Control Points) conditions	Live BSF larvae can be used in combination with local plant proteins to successfully replace soy in diets of older laying hens. Feeding hens live BSF larvae also had a positive effect on the feather condition of birds with intact beaks	Old laying hens	Star et al. (2020)
Partially and highly defatted BSFL meal	Cereal by- products	The collected larvae were dried for 20 h in an oven at low temperature (60 °C) and ground to a meal. High pressure and without solvents method	Defatted BSF meals can be considered as an excellent source of apparent metabolizable energy and digestible amino acid for broilers with a better efficient nutrient digestion	Broiler chickens	Schiavone et al. (2017)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL meal and BSFL fat	Powdered compound feed and vegetarian b-products of the pasta	Harvested larvae, killed (by freezing) and stored at -20 °C. Finally the larvae were washed, dried at 60 °C for 24–34 h depending on the water content, ground and defatted by pressing. A commercial oil press was used	*Hermetia* meal can be a valuable component of layer diets	Lohmann selected Leg-horn laying hens	Maurer et al. (2016)
BSFL oil and meal	NA	NA	BSFL oil and meal can be used as dietary energy, protein and amino acids for hen maintenance, egg production and yolk col-oration, although there may be upper limits of dietary inclusion	White leg horn	Patterson et al. (2021)
BSF protein derivatives	NA	Pasteurization, partially defatted & dried, enzy-matic hydrolyzation	Effective in protecting the animal cells from oxidative damage as a consequence of immune response	NA	Mouithys-Mickalad et al. (2020)
BSF fat	Chicken feed	Fat from Freeze-dried prepupae extracted with diethyl ether	Soybean products (meal and/or toasted beans) can be replaced by BSF without adverse effects on performance	Weaned piglets	Spranghers et al. (2017)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
Partially defatted BSF larva meal	Vegetable by-products substrate	High-pressure Mechanical process without any solvents	partially defatted BSF larva meal can be used as a feed ingredient in diets for weaned piglets without negatively affecting their growth performance, nutrient digestibility, blood profile, gut morphology or histological features	Weaned piglets	Biasato et al. (2019)
BSFL meal (5.0%, 10.0%, & 20%), BSFL oil (2.5% & 5.0%)	NA	partially defatted & dried	BSFL meal and BSFL oil are well tolerated by dogs and their consumption results in no impact on physiology & general health suggesting could be included safely in dog diets	Beagle dog (*Canis lupus familiaris*)	Freel et al. (2021)
BSFL Meal	NA	Freeze-dried, ground, and partially defatted	Including BSFL meal in dog food can be an appropriate source of protein without any negative effects on nutrient digestibility and fecal quality	Beagle dog (*Canis lupus familiaris*)	Abd El-Wahab et al. (2021)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL meal	NA	Dried, defatted	BSFL meal can be supplemented in the diet to convert beneficial effects to beagle dogs, indicated as improved digestibility of dry matter and crude protein and anti-inflammatory and anti-oxidative capacity	Beagle dog (*Canis lupus familiaris*)	Lei et al. (2019)
BSFL meal	NA	Dried, defatted	Digestibility analysis of a dog food containing insect meal as the sole source of protein (36.5% inclusion) showed promising results in terms of it presenting similar values as a meat-based diet, indicating its suitability as a sustainable protein source for pet food	West Highland White Terrier dog (*Canis Lupus*)	Penazzi et al. (2021)
BSFL Meal, Whole BSFL, BSFL oil	NA	killing, drying, and defatting method	BSFL-containing diets are palatable and do not negatively affect fecal characteristics or serum chemistry but may have slightly lower nutrient digestibilities in adult cats	Cats	Do et al. (2022)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL meal	NA	killing, drying, and defatting method	Use of BSFL meal as an unconventional feed ingredient in *Sparus aurata* diet looks promising, although the quality of filets may be affected	*Sparus aurata* (Gilt head bream fish)	Oteri et al. (2022)
BSFL meal	NA	killing, drying, and defatting method	Up to 19.5% of BSFL meal, corresponding to 22.5% of total dietary protein, may successfully replace BSFL meal in diets for juvenile European seabass, without adverse effects on growth performance, feed utilization or digestibility	*Dicentrsrchus labrax* (European seabass)	Magalhães et al. (2017)
BSFL meal	NA	BSFL meal was extracted four times with a 2:1 (v/v) ethyl alcohol (95%) to BSFL meal for each extraction, followed by one extraction of 3:1 (v/v), and a final extraction with a 4:1 (v/v) ratio	In conclusion, the current results give insight into current limitations of using black solder fly larvae meal in white shrimp and possible avenues of expanding insect meal replacement of fishmeal in aquaculture diets	*Litopenaeus vannamei* (Pacific white shrimp)	Cummins Jr. et al. (2017)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL meal	Vegetable by-products substrate	BSFL meal was partially defatted with a mechanical process performed using high pressure and without solvents	Partially defatted HI larvae meal can be used as feed ingredient in trout diets up to 40% of inclusion level without impacting survival, growth performance, condition factor, somatic indexes, dorsal fillet physical quality parameters, and intestinal morphology of the fish	*Oncorhynchus mykiss* (Rainbow trout)	Renna et al. (2017)
BSFL full fat larvae meal	Wheat middlings, fresh vegetable and fruit mix	A batch of BSFL was dried for meal production. The BSFL were dried first at 130 °C for 1 h and then at 80 °C for 23 h until a constant weight was reached using a chamber air flow dryer to produce BSFL meal and stored at 4 °C before use for feed preparation	Moreover, feed acceptance increase was observed in treatments containing than 10% and higher shares of BSFL. In the groups whose feed contained 5 to 30% of BSFL in the diet, the growth of experimental fish as well as their feed utilization parameters were improved; however, with no effects on feed digestibility. All presented data make BSFL a suitable nutrient source alternative to fish meal in Siberian sturgeon nutrition	Siberian sturgeon fingerlings (*Acipenser baerii*)	Rawski et al. (2020)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
BSFL oil	NA	Black soldier fly larvae oil was obtained by cold-press technique	Black soldier fly larvae oil may be considered as a good alternative lipid source in practical diets in Jian carp feeding. 100% of added Soybean oil can be safely replaced by black soldier larva oil (25 g kg – 1 diet) without any negative effect on growth, feed efficiency or nutrient deposition in fish fillets. Moreover, black soldier fly larvae oil improved the content of total n-3 PUFA, while reduced the content of total n-6 PUFA in the muscle	*Cyprinus carpio var. Jian* (Juvenile Jian Carp)	Li et al. (2016)
Partially defatted BSFL meal	NA	Dried, Heat treated, defatted	African catfish can effectively utilize *Hermetia illucens* up to 172 g kg^{-1} (75% FM replacement) without impairing growth, nutrient utilization, antioxidant, and health status of the fish	*Clarias gariepinus* (African cat fish)	Fawole et al. (2020)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
Partially defatted BSFL meal and BSFL oil	Enviroflight LLC feed grade	Sterilized, Dried, and Mechanically pressed to extract the oil from the meal	The digestibility of hydroxyproline was significantly superior. The maximum inclusion of BSFLM recommended in rainbow trout diets is 13%	*Oncorhynchus mykiss* (Rainbow trout)	Dumas et al. (2018)
Full-fat BSF prepupae meal	Vegetable waste	Frozen prepupae were grinded	Findings suggest that caution should be taken into account when 50% replacement of conventional ingredients with Full-fat BSF prepupae meal is selected	*Oncorhynchus mykiss* (Rainbow trout)	Cardinaletti et al. (2019)
Partially defatted BSFL meal	NA	A mechanical process performed using high pressure and without solvents	40% inclusion of BSF larva meal can be used successfully in standard diets for perch	*Perca fluviatilis* (Eurasian perch)	Stejskal et al. (2020)
BSFL meal	Media containing partial seaweed mixed with organic plant-derived waste	Partially defatted, dried and grounded	Study showed that a total replacement of fish meal with black soldier fly larvae meal in the diets of sea-water Atlantic salmon was possible without negative effects on growth performance, feed utilization, nutrient digestibility, liver traits or the sensory qualities of the fillet	*Salmo salar* (Atlantic salmon)	Belghit et al., (2019a, 2019b)

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Table 1 (continued)

Type of animal feed	Feed resources	Processing technology	Uses	Animal species	Reference
Full-fat BSFL meal	Starter feed of broilers	BSFL were dehydrated in a forced air circulation oven at 55 °C for 24 h. Dehydrated larvae were ground in a multiprocessor with 0.8 mm mesh	BSFL meal seems to be a promising source of protein and energy for omnivorous fish aquafeed	*Colossoma macropomum* (Tambaqui)	Monteiro dos Santos et al. (2023)

insects as feed for pets, pigs, poultry, and as aquafeed. Of all feed produced in the world (1.1 billion tons), poultry takes 44.8%, pigs 25.9%, ruminants 22.2%, aquaculture 4.5% and pets 2.6% (Alltech, 2016). In general, it seems that the nutritional composition of insects, such as the high protein, lauric acid omega 6, and omega 3, and bioactive compounds, such as chitin, seems to have potential in animal feeding (Shah et al., 2022). A schematic summary of how animal feed and fertilizer (BSF Frass) is produced from BSF is given in Fig. 2, where the inputs of organic waste are converted by BSFL by artificial rearing in at controlled environment to get outputs as protein meal, lipids, chitin and biofertilizer.

3.1.1 Commercial animal feed versus products derived from BSF larvae

3.1.1.1 Aqua feed By 2030, aquaculture, or fish farming, is anticipated to contribute 62% of the world's fish supply (FAO, 2014). The need of fish for human feeding and depleted fisheries, amongst other factors, have increased the price and driven up the cost of fish meal and oil, forcing fisheries to look for alternatives like vegetable oils despite the fact that it is well acknowledged that they are essential for aquaculture (Li et al., 2016). Fishmeal and fish oil are the main source of protein and essential fats in aquatic feed production. For the manufacture of these, 18 million tons was used in 2018 which is 10% of the total production

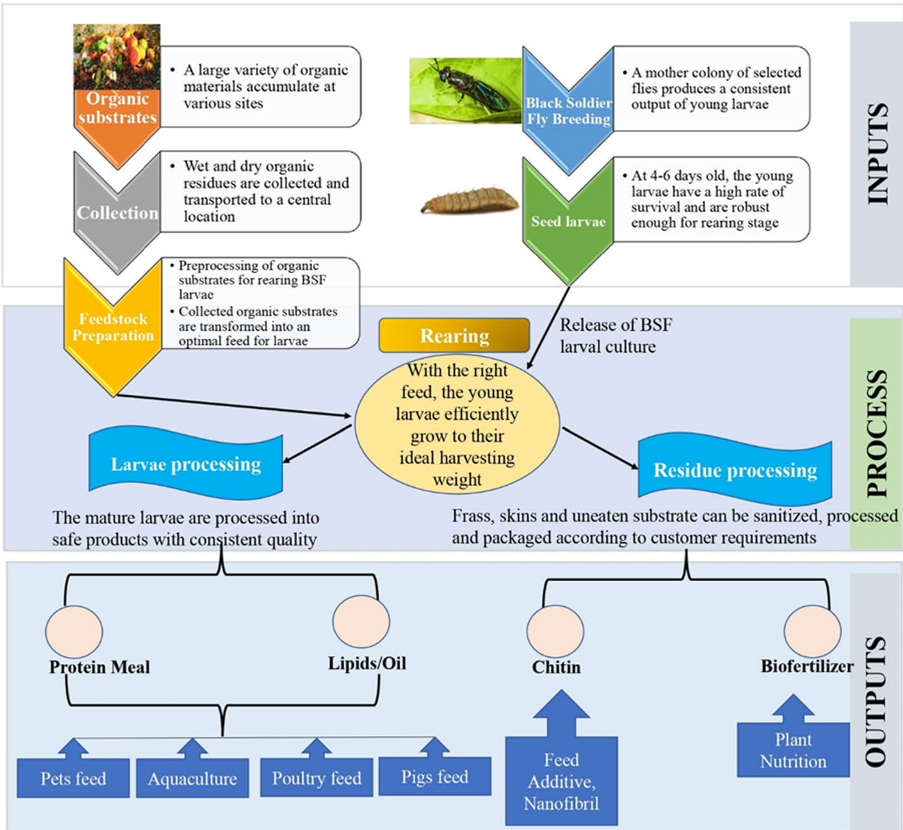

Fig. 2 Schematic summary of how animal feed and fertilizer is produced from Black Soldier Fly treatment

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of world fisheries and aquaculture (FAO, 2020). A major protein source in aquafeeds is soybean meal but its increasing price, poor content of methionine and lysine, and the presence of anti-nutritional factors, especially trypsin inhibitor, is a drawback (Chakraborty et al., 2019; Chen et al., 2019). Processed animal proteins (PAPs) which are allowable to be used in fish feed, are not yet included in many of the feed products on the market today.

Insect protein has similar characteristics to PAPs and provides a good, sustainable alternative. The demand for formulated fish feed presents an opportunity for the insect sector. If given a diet that is sufficiently high in lipids, BSFL can hoard fats in their bodies. Vegetable oils are typically less appetising to fish than BSFL. When fish offal is added to the larval diet, pre-pupae that are enriched in omega-3 fatty acids are formed (St-Hilaire et al., 2007). When related to regular fish meals, these "enriched" pre-pupae are fit fish feeds, producing no appreciable changes in fish development and vision (Oncorhynchus mykiss, rainbow trout) (Sealey et al., 2011). Nairuti et al. (2021) reviewed several studies for possible replacement levels of fishmeal with BSF meal and this ranged from 10% for meager juveniles (*Argyrosomus regius*) to 25% for Siberian sturgeon (*Acipenser baerii*) and pacific white shrimp (*Litopenaeus vannamei*), 50% for European sea bass (*Dicentrarchus labrax*) to 100% for Nile tilapia (*Oreochromis niloticus*).

According to sensory investigation of trout fillets, fish given fish meal, BSFL, or enriched BSFL diets did not differ in any manner (Sealey et al., 2011). One more study on rainbow trout (Renna et al., 2017) suggested supplementing the diet with up to 40% defatted BSFL with no contrary effects on the physical quality of the fillet or the fish's physiology, but they did notice a drop in beneficial polyunsaturated fats. In another study on rainbow trout, the top limit for BSFL in the diet for unaffected fish growth was determined at 15% (Renna et al., 2017). No differences in growth performance between BSFL oil and soybean oil were detected in a study on young Jian carp (*Cyprinus carpio* var. Jian), but it was found that as BSFL oil's share of the diet increased, carp lipid deposition decreased (Li et al., 2016). After trials with the African catfish, *Clarias gariepinus* demonstrated that total BSFL replacement of fish meal in diets (where it made up just 25%) had no consequence on development rate and nutrient utilisation indicators, BSFL were proposed as an alternative due to their lower cost.

Finally, BSFL can considerably contribute to sustainable aquaculture as a partial or full meal replacement, for aquatic invertebrates like prawns (Cummins et al., 2017). This is the conclusion reached by numerous writers. This is due to BSFL's capacity to transform potentially low-protein organic wastes into protein-rich edible biomass. Tran et al. (2024) reviewed 107 studies dealing with 23 freshwater and 17 marine fish species, and 17 insect species as a replacement for fishmeal. While in general high levels of BSF seem to depress fish growth (Hua, 2021). The major factors limiting inclusion of insects in aquafeed are: reduction in protein digestibility, imbalanced amino acid profile and increasing levels of saturated fatty acid (Liland et al., 2021). Although Quang Tran et al. (2022) consider insect meal as an excellent potential to supply protein for aquafeeds, they recommend addressing nutritional composition and environmental aspects and developing suitable insect-specific substrates as aquafeed.

Future research should focus on nutritive values of different insect species and the necessity to identify optimal levels for different types of insect meals. In July 2017, insect proteins from seven insect species were authorised in the EU for use in aqua feed, opening new feed markets for insect producers. Like other farmed animals, these insect species may only be fed with 'feed grade materials' such as materials of plant origin, processed eggs, milk and their derived products. Above 5000 tonnes of insect protein have been commercialised by European insect producers in total, since the authorisation of insect proteins

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for use in aqua feed. Today, the aqua feed market consumes more than 50% of European animal feed made from insects and this is expected to increase in the coming years (Liland et al., 2021).

3.1.1.2 Poultry feed Today insect proteins cannot be fed to poultry in European Union as legislation passed after the BSE (bovine spongiform encephalopathy) crisis in the late 1990s prevents processed animal proteins from being fed to livestock. Only fishmeal may be used and yet, over 90% of EU insect feed producers see poultry feed as a ‘promising opportunity’ (IPIFF, 2018). Dörper et al. (2021) concluded that partial replacement of soybean meal by larvae of BSF or housefly in feed is beneficial for poultry. Chodova and Tumova (2020) reviewed a number of studies, and identified that insect meals can have a positive influence on growth of chickens without adverse impact on carcass and meat quality characteristics.

BSFL has been used in poultry feed as an incomplete replacement for maize- or soy-based feeds. The species naturally colonizes and decomposes poultry manure. Where populations of it are routinely maintained by poultry farms for the benefit of waste management and pollution reduction. There was no difference in productive act, breast meat weight, or yield between the control group and either of the two BSFL meal proportions in experiments with grill quails, *Coturnix coturnix japonica* (Cullere et al., 2018). The oxidative status, lipid content, and sensory and flavour judgements of breast meat were unchanged by BSFL supplementation. However, it did increase the meat’s amino acid content, improving its nutritional value (by increasing glutamic acid, alanine, aspartic acid, serine, tyrosine, and threonine). The amounts of undesirable saturated and monounsaturated fatty acids did, however, rise (Cullere et al., 2018).

Similar outcomes were attained by adding BSFL to the feed of domestic broiler chickens (*Gallus gallus*), with the caveat that utilising defatted BSFL diminished the detrimental effects on fatty acid profiles. In both instances (partial or total replacement of soybean oil by BSFL fat), Schiavone et al. (2017) discovered that BSFL was a suitable source of protein for chicken feed, with the authors depicting that BSFL “inclusion definite satisfactory creative performances, carcass traits and complete meat quality” (Schiavone et al., 2017). The health or concert of the laying hens or the quality of the eggs were not affected by the addition of BSFL (50%) or the complete substitution of soybean cake in the diets of the hens (Maurer et al., 2016). As a result, BSFL are a probable partial replacement for poultry feed since they add extra protein and have the added benefit of being able to be raised on the waste of the same animals that will eventually consume them.

3.1.1.3 Pet feed Pet food is a mainstream market for European insect producers. Insect products are well-suited to the particular needs of pet food, due to their high digestibility and palatability. Some European pet food companies already incorporate insects in their feed formula, notably as a means to expand their products’ range e.g. in hypoallergenic products. This trend is expected to continue to grow in the next few years. While only 3% of all feed produced is for pets, 50% of the insect industry is engaged in producing for this sector (van Huis, 2022). In vitro assays displayed that fraction containing BSF larvae protein significantly inhibited the growth of *Clostridium perfringens*, which is for 28% of the cases responsible for diarrhoea in dogs (Dong et al., 2021). However, Bosch and Swanson (2021) caution that health-promoting effects of insect products need to be studied more as well as the long-term impact of insects as food on the nutritional status of dogs and cats. Concerning indispensable amino acids, the limiting ones with BSF methionine and threonine for dogs and the first methionine for cats (Bosch et al., 2019).

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3.1.1.4 Pig feed It is assessed that soybean meal accounts for 85% of the protein supplements fed to pigs (Florou-Paneri et al., 2014). BSF larvae can partly replace soybean meal, and in addition may have interesting functional properties (Kar et al., 2021). The beneficial effects of BSF larvae intake on weaned pigs are diarrhoea reduction, better immune response, and improved small intestinal morphology (Choi & Hassanzadeh, 2019). BSF prepupae are rich in lauric acid, known for its antimicrobial effects on Gram positive bacteria (Spranghers et al., 2017). The amino acid digestibility and growth performance in pigs fed BSF larval meal is analogous to that of soybean meal and fishmeal (Hong & Kim, 2022). In commercial conditions damaging behavior such as tail biting often occurs in post weaning pigs. Providing small amounts of live BSFL daily to piglets after weaning can improve piglet welfare while maintaining piglet performance (Ipema et al., 2021). However, the current price of insect meal is still higher than that of soybean, the reason to explore the potential added value of BSF compared to conventional protein sources.

The necessity to consider different quality factors is a crucial component of successfully introducing insects into the feed chain. In this regard, the extended quality triangle proposed by Luning and Marcelis (2009) defines three quality aspects related to the product itself. This successful introduction of insect protein in feed is thought to depend on these three factors: insect quality as such, insect availability, and costs. Choosing appropriate insect species and strains, locating affordable rearing substrate (if possible by utilising organic waste side-streams, but ensuring feedstock safety when rearing insects on organic waste and manure), managing diseases and establishing sanitation procedures, producing a consistent supply of high-quality insects (including quality assurance), developing innovative and cost-effective production systems, and increasing a crop's yield are the main challenges to using insects as feed. These factors can all be connected to one or more feed chain processes and will be further explored in this text (Veldkamp et al., 2012).

Whereas, insects are the natural component of the diets of animals, such as carnivorous fish, poultry and pigs. They are high in protein from 50 to 82% (as a dry product) and can be added to animal feed with up to 40% insect content for fish feed and 30% for chicken feed. The environmental benefits of insect mass production include low greenhouse gas emissions (van Huis & Oonincx, 2017), the small amount of land required to produce 1 kg of protein (Oonincx & de Boer, 2012), reduced land use due to lower feed-food competition (Makkar, 2018), and the ability to transform organic waste streams into high-value protein products (Meneguz et al., 2018). One innovative strategy and outstanding illustration of a sustainable circular economy is the use of insects in the bioconversion of waste materials (Meneguz et al., 2018). Therefore, it is well recognised that BSFL can be utilised as a substrate for a range of vertebrate wastes and can be used to feed a variety of vertebrates (Tomberlin et al., 2015). This has noteworthy repercussions for low-input, sustainable agriculture in underdeveloped nations (Nyakeri et al., 2017), yet it has no effect on how tasty the meat from BSFL-fed animals is for human consumption. Although the potential assistances are greatest in these developing nations, BSFL and added insect feeds are projected to assume larger roles over time in wealthy nations like the United States due to commitments to minimise waste made by food companies seeking approval from consumers and regulators who are becoming more environmentally sensible, as well as the fluctuating costs of fish meal and other feed driving the producers to pursue alternatives (Klonick, 2017).

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3.1.2 Types of products derived from black soldier fly larvae

3.1.2.1 Dried larvae BSF larvae meals are a valid, cost-effective, and highly nutritive alternative source of animal protein feed (Edea et al., 2022). Sources of protein in animal feed play an important role in forming body tissues and vital metabolism such as enzymes, hormones, antibodies, and so on (Beski et al., 2015). The use of insects as a source of protein has been widely studied and discussed around the world. Protein from insects is known to be more economical, environment friendly, easy for mass production and has high feed conversion efficiency (Van Huis, 2013). They are also part of natural feed for poultry (Makkar et al., 2014). One of the determinants of animal feed quality is expressed in terms of crude protein content and essential amino acids profile based on dry feed ingredients. BSF larvae is an alternative feed protein source that cannot be stored in the fresh form for a long time without drying. Fifteen days old larvae of BSF were dried either using the stove oven drying for 75 min or using 800 Watts of microwave drying for 25 min. The study concludes protein content of BSF larvae, were not significantly different between drying treatments, while the amino acid content was higher in the microwave drying than stove drying method. This study concludes that the above two methods can be used in preserving BSF larvae as a source of dietary protein for farm animals (Purnamasari et al., 2021).

The protein content in larvae of BSF is used as animal feed. Larvae are living materials that, if not treated, will continue to grow into adult flies. In addition, if stored in a dead condition, the larval product will rot because it has a high-water content. Drying is an easy and inexpensive method to extend the shelf life of the product. Drying is a process of hydrating or removing water from material. The purpose of drying is to increase durability, reduce packaging costs, reduce transport weight, improve the taste of the ingredients, and maintain the nutritional content of the ingredients (Achanta & Okos, 2000). Therefore, BSF larvae need proper processing strategies to maintain nutrient content in ingredients, to be able to extend a longer shelf life and, make it easier to be used in formulations of feed ration.

3.1.2.2 Protein meal BSF protein meal has high-quality amino acids, lipids and micro nutrients to boost the animal's health naturally. It fully replaces conventional protein in many dry and wet pet food and aquaculture applications, while adding functional benefits and superior palatability. A well-balanced combination of high-quality amino acids, lipids and micro nutrients, easily digestible proteins (> 85%), superior palatability, high freshness index (BAI < 1), suitable for hypoallergenic diets in pet food, and other functional characteristics (Rawski et al., 2021). The protein content of the insect species is within the soybean/fish meal range and fat content is higher especially compared to (defatted) soybean meal. The pet industry has boomed during the pandemic, with purchase and adoption of pets rising, spending on pets hitting a record in 2020, and the trend so intense veterinarians have struggled to keep up with demand (Hornyak, 2021).

BSFL can be processed in different ways which results in ingredients for the feed industry with different protein and fat contents. The defatted BSFL meal (D-BSFL) is produced by partial or total fat extraction using pressing or organic solvents, and the resulting defatted meal is then posteriorly dried and ground. D-BSFL has around 60% protein and 10–12% lipid content (Barroso et al., 2014; Monteiro dos Santos et al., 2023). The full-fat BSFL (FF-BSFL) meal is easy to produce by drying and posteriorly grinding. The FF-BSFL is a low-cost technology when related to D-BSFL as it avoids expenses associated with fat extraction processes. FF-BSFL has an average content of 42% crude protein and

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30% lipids (Magalhães et al., 2017; Veldkamp et al., 2012). Insects as feed ingredients for aquafeeds are on the rise in science and industry sectors, since there is an emergent necessity for alternative protein sources to fish meal and fish oil (Rawski et al., 2021).

3.1.2.3 Oil Insect lipid that provides a quick source of energy due to high levels of easily digestible medium-chain fatty acids. contains 40% lauric acid, which is recognized for its antimicrobial properties in the digestive tract. A healthy gut means a stronger immune system. is an especially valuable energy source for younger animals that suffer from digestive problems and have impaired nutrient absorption. The animals grow healthy while the industry reduces its ecological footprint.

Oil extraction efficiency could be improved by acid hydrolysis prior to down-stream processing of BSFL. The separated oil from conventional down-stream process has a high content of trilaurin giving a melting point at 26 °C that may cause technical issues for some feed and food applications. Lower trilaurin content and melting point can be achieved by acid hydrolysis of BSFL and/or winterization of the oils. This will allow producers of BSFL to tailor oil properties to various markets (Bogevik et al., 2022). BSFL oil is dominated by a few fatty acids (mainly 12:0, lauric acid) (Ushakova et al., 2019) which limit its inclusion levels in cold-water aquaculture feeds. These feeds normally include fish oil and rapeseed oil with a large distribution of fatty acids including polyunsaturated acids. Replacement of corn oil with BSFL oil at 0, 4, 6 and 8% showed a linear increase of growth in nursery pigs (Heugten et al., 2019). In addition, lauric acid from BSFL demonstrated antimicrobial properties on gastrointestinal bacteria. While 5% inclusion of BSFL oil to a basal broiler chicken diet had no effect on growth, 50 and 100% replacement of soybean oil with BSFL oil reduced growth in broiler chickens (Kim et al., 2020). In a diet to rainbow trout (*Oncorhynchus mykiss*), replacement of fish oil with BSFL oil had no effect on growth (Kim et al., 2020). Increased inclusion of BSFL meal or oils in diets has generally caused increased saturated fatty acid content in edible meat products. The content of saturated fatty acids in meat is closely related to the texture (Belghit et al., 2019a, 2019b). Thus, an increased ratio of polyunsaturated fatty acids is more desirable both for meat quality and human health (Hong et al., 2013; Wood et al., 2004) Nevertheless, the high saturated fatty acid content of the BSFL could be beneficial in terms of energy and antimicrobial activity (Świątkiewicz et al., 2016).

3.2 Frass as fertilizer

According to Commission Regulation (EU) 2021/1925, frass is defined as a mixture of excrements derived from farmed insects, the feeding substrate, parts of farmed insects, dead eggs and with a content of dead farmed insects of not more than 5% in volume and not more than 3% in weight (EU, 2021). A large variety of organic waste streams (e.g. manure, food waste, biogas slurries) can be converted by BSF larvae into new insect biomass and the residual fraction is called frass (Elissen et al., 2023). The composition of the produced frass is variable depending on the composition of the substrates (Elissen et al., 2023) especially P, K and micronutrient concentrations (Lopes et al., 2022). Frass can contain significant amounts of N, P, K, organic matter and other components such as chitin (from the larvae skins). Beesigamukama et al. (2022) concluded that BSF frass has significantly higher N (20–130%) and K (17–193%) concentrations compared to frasses of other insects. However, frass is a biologically unstable product, due to its rapid breakdown and the presence of substances with potential phytotoxic properties. As a P dominated

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fertilizer, N supplementation is necessary to make BSF frass a more balanced fertilizer product (Lopes et al., 2022). The frass can be used for different applications: direct or composted as fertilizer or soil conditioner, or for biogas production (e.g. Bulak et al., 2020; Hol et al., 2022). BSF frass application led to the highest seed germination rate/index (Beesigamukama et al., 2022). Table 2 highlights the nutrient composition of BSF frass obtained by using different organic wastes.

3.2.1 Commercial fertilizer versus black soldier fly frass

The world-wide agricultural industry is confronted with numerous issues. According to the UN, by 2050, the world population will have surpassed nine billion people. This will put a lot of pressure on agricultural business, which is already suffering from a loss of productivity. Farmers are forced to use fertilizers to enhance their agricultural output due to loss of arable land across the globe and to meet requirement of growing population (FAO, 2017). Being expensive, the organic and synthetic fertilizers can't be affordable by farmers. Many of the organic fertilizers supply limited nutrients and release the nutrients slowly (Shaji et al., 2021). Synthetic fertilizers are toxic to the skin and respiratory system and damage the plants and reduce soil fertility by easy washout of nutrients and also cause eutrophication. This paves a way to use insect frass as potential fertilizer. In fact, the capacity of frass to supply nutrients to plants and enhance plant growth has been compared to that of synthetic fertilizer and its potential to replace conventional fertilizers has been pointed out (Houben et al., 2020).

It's a relatively recent idea to use insect BSF frass as organic fertilizer. Any farming system that uses a novel idea or product as fertilizer has to know how it performs in terms of how it affects crop development, yield, nutrient uptake, and usage efficiency in comparison to other fertilizers. The source, nutrient content, mineralization stage, and storage technique of organic fertilizers all have a significant impact on their efficacy (Ebanyat, 2009; Ndambi et al., 2019; Rufino et al., 2007). For instance, the source, mineralization level, and C/N ratio of manure all have a significant impact on the availability of nutrients (Grigatti et al., 2015; Musyoka et al., 2019). BSF frass being an organic fertilizer is comparable to poultry manures but it has low nutrient contents compared to high-value commercial organic fertilizers (Gärttling & Schulz, 2022). Organic matter content of BSF frass is higher than all other manure and compost types. N content and C/N ratio are closest to the values of cow slurry, while P content is most comparable to that of pig slurry and K content is most comparable to that of poultry manure (Gärttling & Schulz, 2022). Relatively low C/N ratio (13–16 on average) of BSF frass paves a way for easy nutrient uptake (Beesigamukama et al., 2021a) and pH of 6–8 which is a good value for mature compost for agronomic purposes (Basri et al., 2022). C/N ratios of BSF frasses from cow, chicken and pig manure usually tends to be lower than 20, which is indicative of a mature compost (i.e. lower than 25 according to the authors). In addition, germination indexes and nutrient concentrations of all frasses are more than their respective manure (Liu et al., 2019).

In comparison to urea and SAFI (a combination of chicken manure, charcoal, and rock phosphate), BSF frass as fertilizer is more successful in increasing yield when applied to maize at rates of 2.5 t ha^{-1} and 30 kg N ha^{-1}, respectively, while SAFI needs to be applied at double the rates to get the same yield. Plots treated with BSF frass display the tallest plants, maximum chlorophyll concentrations, and higher nitrogen recovery efficiency. In comparison to the value obtained with an equivalent rate of SAFI, the agronomic N usage efficiency and nitrogen fixing efficiency of maize treated with 2.5 t ha-1 of BSF frass are

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Table 2 Overview of various organic wastes attributes to black soldier fly composition

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
	175 g/kg	140 g/kg	8 g/kg (determined as nitrogen free extract)	9.3 g//kg				Finke (2013)
Poultry manure	34–35%							Zhou et al. (2013)
Cow manure	34–35%							Zhou et al. (2013)
Waste	42–49%	38%						Makkar et al. (2014)
Chicken, pig and cow manure					13.5–30.3 g/kg	9.9–39.4 g/kg		Oonincx et al. (2015)
Processed food wastes or brewery spent grains					29.5–33.2 g/kg	103–149 g/kg	31–19 g/kg	Devic (2016)
Mix of fruits, vegetables, seaweeds					2.45 g/kg	0.69 g/kg	2.62 g/kg	Mason (2016)
100% Brown Algae	41.3 ± 1.1%	8.1 ± 0.9%		15 g//kg				Liland et al. (2017)
Fruits waste	35–58%	15–38%						Mohd-Noor et al. (2017) and Nyakeri et al. (2017)
Human manure	45%	18%						Nyakeri et al. (2017)
Fruit/vegetable wastes	39%	33%						Nyakeri et al. (2017)
Organic municipal waste					14.9 g/kg	9.8 g/kg	10.3 g/kg	Salomone et al. (2017)
organic waste substrates	431.0 g/kg	386.0 g/kg		1.2 g/kg				Spranghers et al. (2017)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Municipal organic solid waste	36–46%	25–39%						Sprangers et al. (2017) and Nyakeri et al. (2017)
Vegetable wastes	44%							Tinder et al. (2017)
Chicken manure					28 g/kg	14.4–19.8 g/kg	22.4–24.0 g/kg	Xiao et al., (2018a, 2018b)
Food waste, chicken feaces and saw dust (3:2:1)					1.7%	1.1%	2.1%	Attiogbe et al. (2019)
Food waste	24							Ermolaev et al. (2019)
Maize straw					4.8%	1.0%	0.9%	Gao et al. (2019)
Chicken, cow and pig manure					17.9–18.7 g/kg	9.6–27.0 g/kg	13.9–21.2 g/kg	Liu et al. (2019)
Municipal organic solid wastes from domestic, markets and restaurant					3.6–4.8 mg/kg	0.8–0.9 mg/kg	0.54–0.62 mg/kg	Sarpong et al. (2019)
Wheat bran, alfalfa meal, corn meal					44 g/kg	22.7 g/kg	34 g/kg	Setti et al. (2019)
Organic waste streams	411.0 g/kg	301.0 g/kg		1.9 g/kg				Shumo et al. (2019)
Brewary spent grain					2.1%	1.2%	0.2%	Beesigamukama et al. (2020b)
Food processing waste					19.8–23.7 g/kg	5.3–6.4 g/kg	9.3–13.9 g/kg	Bestico (2019/2020)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Chicken manure, chabazite					26.6 g/kg	11.9 g/kg	67.2 g/kg	Bortolini et al. (2020)
Carrot/beetroot waste					22.1 g/kg			Bulak et al. (2020)
Pig manure					14.7 g/kg	66.9 g/kg	20.3 g/kg	Cai et al. (2020)
Unknown					33.0 g/kg	14.9 g/kg	24.0 g/kg	Gärttling et al. (2020)
Household waste					2.2%	0.1%	0.1%	Kawasaki et al. (2020)
Chicken feed, grass-cuttings, fruit/vegetables frass					18.3 -25.9 g/kg			Klammsteiner et al. (2020)
Almond by-product (hulls and shells), amended with urea					12.3–22.3 g/kg			Palma et al. (2020)
Organic waste streams	411.0 g/kg	301.0 g/kg		1.9 g/kg				Shumo et al. (2019)
Wheat yeast concentrate, by-product from wheat and potato, binding agent					29.4 g/kg	5.7 g/kg	20.2 g/kg	Parodi et al. (2020)
Okara and wheat bran					3.2–4.8%	0.8–1.2%	0.5–0.9%	Song et al. (2021)
Brewer's spent grains					36.1 g/kg	5.0 g/kg	2.9 g/kg	Anyega et al. (2021)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Okara					51.5 g/kg	0.29 g/kg	1.9 g/kg	Chiam et al. (2021)
Spent coffee grounds and donut dough					42 g/kg	3.1 g/kg	6.3 g/kg	Fischer et al. (2021)
Chicken manure					4.3 mg/kg	3.8 mg/kg	3.0 mg/kg	Guo et al. (2021)
Onion and potato by-products					28.1 g/kg	15 g/kg	33 g/kg	Menino et al. (2021)
Pre-consumer urban food waste					32 g/kg	8.7 g/kg	8.7 g/kg	Nicksy et al. (2021)
Pre-consumer vegetable wastes or brewer's spent grains/spent coffee grounds					26.5–38.6 g/kg	2.8–9.3 g/kg	2.1–47.6 g/kg	Rummel et al. (2021)
Restaurant waste or okara					31.5 g/kg	0.39 g/kg	1.33 g/kg	Tan et al. (2021)
Brewery spent grains					50–36 g/kg	9.3–5.0 g/kg	2.2–2.9 g/kg	Tanga et al. (2022)
Wheat bran	2.8%				19.77 g/kg	22.36 g/kg	0.47 g/kg	Watson et al. (2021)
Fruit/vegetable/bakery waste-based diet with brewery waste, Gainesville (GV) reference diet					20.1–27.0 g/kg	12.7–19.4 g/kg	29.7–36.5 g/kg	Arabzadeh et al. (2022)
Hemp waste					20.2 g/kg	7.1 g/kg	14.8 g/kg	Banavar et al. (2022)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Different food wastes					6–48 g/kg	0.4–10.9 g/kg	0.8–17.4 g/kg	Basri et al. (2022)
Spent malted barley grain					31.6 g/kg	5.6 g/kg	2.7 g/kg	Fuhrmann et al. (2022)
Combinations of potato waste, brewing byproduct, mushroom stalk, orange/mandarin/clementine waste, beetroot peelings, chicken feed waste, vegetable food wastes collected from supermarkets, commercially available frass made from general food waste					20–34 g/kg			Gebremikael et al. (2022)
80% potato waste + 20% brewing by-product (BG)					2.3%DW			Gebremikael et al. (2022)
40% potato waste + 40% mushroom stalk + 20% BG					3.4%DW			Gebremikael et al. (2022)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
80% orange/mandarin/clementine waste + 20% BG					3.3%DW			Gebremikael et al. (2022)
40% orange/mandarin/clementine waste + 40% beetroot peelings + 20% BG					3.4%DW			Gebremikael et al. (2022)
100% chicken feed waste					2.9%DW			Gebremikael et al. (2022)
100% vegetable food wastes collected from supermarkets					2.5%DW			Gebremikael et al. (2022)
Commercially available frass made from general food waste					2.0%DW			Gebremikael et al. (2022)
A liquid anaerobic digestate made from food waste					5.1%DW			Gebremikael et al. (2022)
Potato pulp powder from starch-processing industries					1.0%DW			Gebremikael et al. (2022)
Waste					3.35 36.1 g/kg	1.50 36.1 g/kg	2.99 36.1 g/kg	Gärttling and Schulz (2022)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Brewery waste					35 g/kg	20 g/kg	10 g/kg	Hodge and Conway (2022)
Raw vegetable and fruit waste, hot-pressed rapeseed cake, rye/wheat bread, canola oil, catering waste					79 g/kg	2.4 g/kg	0.1 g/kg	Lanno et al. (2022)
Gainesville diet, distiller's grains, brewery spent grains, okara and wheat bran, household waste, wheat bran, chicken, pig and cow manure, chicken feed, grass, fruits and vegetables, fresh okara					18–51 g/kg	3–52 g/kg	2–41 g/kg	Lopes et al. (2022)
Agro-industrial waste					29 g/kg			Nurfikari (2022)
Different types of organic fraction of municipal solid waste					20–25 g/kg			Papa et al. (2022)
NA					30.8 g/kg	8.0 g/kg	19.9 g/kg	Postma et al. (2022)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Spoiled fish feeds with or without cardboard					87–91 g/kg	20–21 g/kg	12 g/kg	Romano (2022)
Spent coffee, dough, spoiled fish feeds, and a mixture of fruits/vegetables					62 g/kg	14.4 g/kg	17.6 g/kg	Romano et al. (2022)
Decanter cake, palm kernel expeller from palm oil processing					16.4 g/kg			Visvini et al. (2022)
Enviroflight frass					34 g/kg	8 g/kg	11 g/kg	Yildirim-Aksoy et al., 2022
Food industry byproducts						14.6 g/kg	25 g/kg	Protix (2023)
Animal manure	39.1–45.7%	29–35.1%						Kimmy Farm (2020)
Food Wastes	39–41.8%	27.2–35.1%						Kimmy Farm (2020)
Green Waste	31.2–36.4%	5.2–6.63%						Kimmy Farm (2020)
Raw Rice Bran	42.3–45.7%	27.5–27.8%						Kimmy Farm (2020)
Cattle Manure	42.1%	29–34.8%						Kimmy Farm (2020)
Poultry Manure	39–41.8%	27.2–35.1%						Kimmy Farm (2020)
Pig Manure	43–43.6%	26.1–34.2%						Kimmy Farm (2020)
Rice Bran Flour	42.3–45.7%	27.5–27.8%						Kimmy Farm (2020)
Chicken Food	42.8–54.7%	14.6–19.1%						Kimmy Farm (2020)
Fish Waste	60–62.7%	22.5–27.7%						Kimmy Farm (2020)

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Table 2 (continued)

Type of organic waste	Nutrient content				BSF frass composition			Reference
	Protein (% dry weight)	Fat (% dry weight)	Carb	Calcium	N	P	K	
Waste Fish Guts	51.2–57.9%	30.2–340.6%						Kimmy Farm (2020)
Vegetable / organic waste	31.2–36.4%	5.2–6.63%						Kimmy Farm (2020)
Organic waste	50%	35%		2.8–6.2%				Kimmy Farm (2020)

2.4 and 2.5 times greater, respectively (Beesigamukama et al., 2020a). But, composition of BSF frass is highly variable (especially regarding micronutrients) and needs to be assessed on an individual basis for specific purposes (Gärttling & Schulz, 2022) and frass cannot be applied at high concentrations, possibly due to ammonia toxicity (Gärttling et al., 2020). High conductivity values and sodium content are also the drawbacks for application (Chavez & Uchanski, 2021). Thus, it is recommended by Chavez and Uchanski (2021) that insect frass in mixture with inorganic fertilizers can be used for best results on crop and pathogen/disease resistance with a typical effective dosage of 10–40% of the total fertilizer volume administered.

Hopeful evidences on how the BSF frass affects the plant growth and development by modifying the factors such as better use efficiency of P and K (Putra et al., 2017), improved soil fertility and defence against pathogens (Choi & Hassanzadeh, 2019), suppression against *Pythium ultimum* (Ellison et al., 2019), influence on soil N availability (Kagata & Ohgushi, 2012), stimulation of soil microbial activity and diversity (Houben et al., 2020), not impairing hygienic properties of soils (Klammsteiner et al., 2020), improvement of beneficial microbial activity (Houben et al., 2021), increased dehydrogenase activity (Menino et al., 2021), and increased enzyme activity (dehydrogenase and β-glucosidase) (Esteves, 2020) are reported by many authors. Some pot tests have shown the potential of BSF frass, obtained from substrates of various kinds in reducing mineral fertilization in several crops like lettuce (Esteves, 2020; Kebli & Sinaj, 2017), ryegrass (Kebli & Sinaj, 2017; Klammsteiner et al., 2020), maize (Beesigamukama et al., 2020b), *Brassica olaraceae* (Wantulla et al., 2023) and swiss chard (Chirere et al., 2021).

In terms of N, P, K, and organic matter, Choi et al. (2009) compared BSF larvae frass with a commercial fertilizer (unspecified origin) for Chinese cabbage and found that both fertilisers were equally effective (same number of leaves, leaf length and width, and nutrient accumulation), with the exception of P absorption by plants, which was low when fertilized with BSF frass. Wantulla et al. (2023) reported that soil amendment with BSF frass almost halved *Dalia radicum* fly emergence from the soil by the action of chitinase enzyme as compared to the synthetic fertilizer treatment in *Brassica olaraceae* plants and thus increased the yield by reducing the damage. When exposed to tiny amounts of BSF exuviae, *Brassica nigra* displayed larger plants, more blooms, more pollinators, and eventually more seeds (Barragan-Fonseca et al., 2017). Stronger growth, as demonstrated in lettuce plants that thrived when exposed to BSF frass, may be the cause of this impact (Putra et al., 2017; Setti et al., 2019). Alattar et al. (2016) tested BSF larval frass as a fertilizer for maize plants, using a 1:2 (w/w) frass to soil mixture, without mentioning the nutrient composition of the frass and reported that frass impacted plant growth (dwarf plants and fewer leaves) more negatively than did a micro-aerobic fermentation product made from the same feed substrate (food waste) used to feed the larvae.

According to the authors, the reduced growth could be caused by the high concentrations of ammonia in the frass. BSF frass delivered poor growth results (yield, dry matter production, leaf area and nutrient use efficiency) in maize when compared with other by-products (larval skins and dead adult flies) and the controls (organic and chemical commercial fertilizers) (Gärttling et al., 2020). The author attributed the poor fertilization property to the frass being a P-dominated fertilizer, rather than a N-dominated. In addition, the poor growth of the test crop was indicative that the frass may not have an optimal nutrient composition for certain crops. Kawasaki et al. (2020) assessed the fertilizing potential of BSF larvae frass in *Brassica rapa* and recommended an application rate of 1/20–1/30 of frass in relation to the amount of soil, in order to benefit growth, as plant growth was impaired with yellow leaves when applied at a higher application rate (1/10). Quilliam et al. (2020) tested

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BSF larvae frass made from poultry waste, brewery waste and green market waste as fertilizers for growing maize, pepper and shallots in a field experiment in Ghana and reported that amendment of soil with frass bio-fertilizer had no significant effect on yield. This may have been due to the more diffuse broadcast application method that was used and limited the availability of key nutrients at crucial stages of crop development (Fatondji et al., 2009). Chiam et al. (2021) tested okara-derived BSF larvae frass as a fertilizer for lettuce plants, mixing frass with soil at 10, 20 and 30% concentrations (v/v).

Interestingly, the general application (20–30%) of frass resulted in poor growth of lettuce, except for when the frass level was at 10%. The authors speculated that this undesired growth response at high frass levels may be attributed to the low C/N ratio of the fertilizer (7.2), which induced rapid mineralization of nutrients in the soil. Plants with the highest chlorophyll concentrations, increased mineral N concentration, highest maize grain yield and 27% more P accumulation than SAFI fertilizer was observed in maize when treated with BSF frass (Beesigamukama et al., 2020b). When BSF larval frass was used as fertiliser, Menino et al. (2021) saw consistent growth, increased biomass, and increased overall ryegrass yield. Along the plant cycle, however, shoot biomass also decreased significantly. Soil's immobilisation of nutrients and the stimulation of microbial activity, as indicated by the rise in dehydrogenase activity may be the possible reasons for the results. Kale plants grew to much larger heights and produced more leaves after being treated with 100% BSF Frass as Fertilizer (BSFFF). The tallest kale plants were grown using a daily irrigation schedule combined with 100% BSFFF, and the maximum chlorophyll concentrations were attained in the leaves of kale and Swiss chard when 50% BSFFF + 50% NPK or 100% BSFFF were applied. Kale and Swiss chard grown in soil modified with BSFFF had the lowest insect infestation rates and significantly higher fresh shoot weight and leaf dry matter than kale and Swiss chard cultivated in soil without fertilizer. In comparison to NPK treatments, soil amendment with BSFFF preserved higher levels of kale (41–50%) and Swiss chard (33–49%) leaf dry matter during times of water stress (Abiya et al., 2022).

3.2.2 Benefits of black soldier fly frass

Numerous characteristics make the frass of BSFL interesting for use in our overworked agricultural system. It offers similar application potentials as a soil fertiliser to currently available products, but with a lesser impact on the environment (Gärttling & Schulz, 2022; Smetana et al., 2019). Specific components of the insect by-products, such as exuviae acts as bio-stimulants for plants that come in contact with them (Zande et al., 2023) In terms of profitability, producing the frass can be more advantageous than making biogas or composting because in addition to producing frass, the process also creates proteins, lipids, and other goods that can be sold for more money than the soil conditioners and gas produced by the other two production processes. Below we outline a few advantages of adopting BSF frass as fertilizer.

3.2.2.1 Contain chitin BSF larvae contain 14.5% (DM) and the pupae contain 18% chitin (Coudron et al., 2019) which is non-toxic, biodegradable linear polymer said to have fungicidal and nematicidal effects (Gärttling et al., 2020) and can induce plant defence mechanisms against insects. Chitin being the main component of BSF exoskeleton reported to induce beneficial changes in the soil micro biome by increasing the numbers of chitin-degrading bacteria (e.g. some Gamma proteobacteria) frass amended soils (Nurfikari, 2022) and thus stimulate ecological systems by reducing pest pres-

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sure. Many researches pointed out that chitin is protecting crops from pests, pathogens and physiological disorders. Modes of action include antibiosis and induction of plant defences. A number of cell surface receptors, including the macrophage mannose receptor, toll-like receptor 2 (TLR-2), and Dectin-1, have been found to be involved in the recruitment and activation of innate immune cells as well as the induction of the production of cytokines and chemokines by chitin (Lee et al., 2008). Higher chitinase activity in the soil is linked to chitin in the frass. Chitin is also a major component of the cell wall of fungi and is thus prone to degradation by chitinase enzymes (Nagarajkumar et al., 2004) and therefore the frass shows antifungal behaviour (Zhang & Yuen, 2000). It is reported that frass and digestates from pig slurry treatments significantly suppressed the development of *Rhizoctonia solani* in bean plants (*Phaseolus vulgaris* cv. *Prelude*) (Gebremikael et al., 2020) and adding BSF exuviae to Brussels sprouts boosted the influx of parasitoid wasps from the neighbourhood, which fought against crop pests (Zande et al., 2019).

3.2.2.2 Promote beneficial microorganisms The microbiological compositions of organic fertilizers could benefit more sustainable production systems and has been noted that soil amendment with insect frass could stimulate the activity of beneficial microbes (Poveda et al., 2019) and sustain the microbial biomass for a more extended period (Zhang et al., 2020) even under limited nutrient conditions (Gebremikael et al., 2020). Due to the chitin content of the frass and easily degradable components with high N content, numbers of chitin-degrading bacteria (e.g. some Gamma proteobacteria) and some fast-growing high N containing fungi (e.g. Mortierellomycota) can be found in frass amended soils. The beneficial micro-biota of frass also include *Sporosarcina* spp., *Corynebacterium* spp. and *Bacillus* spp. (Kawasaki et al., 2020), *Lactobacillus* spp., *Bacillus* spp., *Actinobacteria* spp., and *Pseudomonas* spp. (Ahemad & Kibret, 2014; Babalola, 2010; Lugtenberg & Kamilova, 2009) and PGPR (Abbott et al., 2018; Ahmad et al., 2020; Pathania et al., 2020; Pérez-Montaño et al., 2014; Treonis et al., 2010) and the microbial composition changes according to the feed substrate supplied to the larvae (Gold et al., 2020; Wynants et al., 2019). These microorganisms act in the rhizosphere, which is the fine region of soil that is influenced by the secretions of plant roots (root exudates) and can be stimulated by the input of organic fertilizers, benefiting the soil and the plant as a whole (Berendsen et al., 2012; Lugtenberg & Kamilova, 2009). The presence of valuable microorganisms in the soil develops higher nutrient use efficiency, improve soil quality, resistance to abiotic stress conditions and improve plants growth, performance and crop yields (Balestrini et al., 2017; Mącik et al., 2020; Poveda et al., 2019).

3.2.2.3 Rich in nutrient content The characteristics of frass from BSF larvae reported in literature indicated that it is a rich source of plant nutrients. The total C, N, P and K content in the frass vary from 26. 8–48.8%, 1.8–5.1%, 0.5–5.2% and 0.2–4.1% respectively (Lopes et al., 2022) depending upon the feed substrate used during the larval growing period (Table 2). It also contains the secondary nutrients like calcium (0.2–45 g/kg), magnesium (0.2–10.5 g/kg) and sodium (0.3–5 g/kg), and also the micronutrients like iron (3.7–600 mg/kg), copper (0.7–46.1 mg/kg), manganese (0.2–149 mg/kg) and zinc (0.1–140 mg/kg) in appreciable quantities which promote very good plant growth and development and thus significantly yield higher crop yield (Lopes et al., 2022).

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3.2.3 Physiochemical properties of BSF frass

3.2.3.1 Moisture content The moisture content of the BSF frass varies from 30% from brewery spent grain substrate (Beesigamukama et al., 2020b) to 72% from the food waste, chicken faeces, and sawdust mixture (3:2:1 ratio) (Attiogbe et al., 2019). The moisture content of other commercial fertilizers varies from 30 to 61% (Basri et al., 2022). The beneficial effect of BSFL frass with low moisture content is good for soil aeration and solubility; on the other hand, the BSFL frass with high moisture content could have inadequate oxygen supply for the plant (Klammsteiner et al., 2020), have adverse impact of BSFL frass leachates, could also cause ammonia poisoning in the plant and may stunt plant development (Zahn & Quilliam, 2017). High moisture content of frass can lead to anaerobic conditions and should be post-processed to be further degraded, for example by composting or anaerobic digestion (Klammsteiner et al., 2020).

3.2.3.2 pH The pH of BSFL frass from various food waste ranges from the lowest of 5.6 in fruit and vegetables (Klammsteiner et al., 2020) to the highest as 8.0 pH value in mixture of food waste, chicken faeces, and sawdust (3:2:1 ratio) (Klammsteiner et al., 2020) and maize straw substrates (Gao et al., 2019). The pH of BSFL frass typically ranges between 7.0 and 8.0 which is comparable with other commercial fertilizers (pH 6—8.1) and is the optimum range for promoting plant growth (Surendra et al., 2020) and providing a conducive environment for the beneficial bacterial communities in BSFL frass (Choi & Hassanzadeh, 2019).

3.2.3.3 Temperature Temperature is an essential factor in determining whether decomposition proceeds at the mesophilic or thermophilic level, or even reaches the maturity level to generate natural plant fertiliser (Kamaruzzaman et al., 2018). BSFL frass temperature ranges from 24 to 27 °C ((Attiogbe et al., 2019; Basri et al., 2022; Sarpong et al., 2019), when compared to the temperature of other composts viz., compost from windrow composting (26–28 °C), composting bin (30 °C), and aerated composting (32 °C); all reach an ambient temperature and is considered to have entered maturation phase (Hamid et al., 2019; Ho et al., 2022). The temperature of the BSF composting is mesophilic and the aeration can be improved on the compost system by the movement and natural turning of the waste by the larvae (Sarpong et al., 2019). As suggested by Cooperband (2002), the optimum temperatures for bacterial decomposition are at 21–49 °C. While, other researchers have reported that high temperature (i.e. 45 °C or more) could cut down the pathogenic loads of the final compost (Banks, 2014; Dortmans, 2015; Tirado, 2008). As temperature is one of the important factors which affect the nutrient availability (Pang et al., 2020) and optimum waste consumption by BSFL, maintaining relatively constant waste temperature (about 30 °C) is inevitable (Pang et al., 2020). Rearing BSFL at the optimum temperature improves their ability to reduce Escherichia coli (Liu et al., 2008). Chen et al. (2019) stated that the continuous movement of BSFL could reduce the BSFL frass temperature, which helps retain nitrogen in the BSFL frass and ensure a high nitrogen content in the BSFL frass.

3.2.3.4 C/N ratio The C/N ratio of BSFL frass derived from different types of food may range from 8:1 to 27:1; kitchen waste range from 8:1 to 17:1, municipal food waste range from 8:1 to 9:1, household food waste at 17:1, fruits and vegetables at 27:1, okara and wheat bran at 8:1 (fresh frass), okara and wheat bran (composted frass) at 10:1, and brewery spent grain at 17:1 (Lopes et al., 2022). In a well-conducted composting process, the C/N will decrease constantly due to the biological mineralization of carbon compounds and loss as

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CO_2 (Insam et al., 2007). Compost with a C/N ratio higher than 30 is more likely to immobilize nitrogen for plant uptake (Sarpong et al., 2019). BSF frass has a relatively low C/N ratio (13–16 on average) and thus makes the nutrients easily available for plant uptake (Basri et al., 2022). C/N ratio can be increased by providing substrates like brewery spent grains with sawdust to BSF larvae (Beesigamukama et al., 2021b). Liu et al. (2019) found that the C/N ratios of frasses from cow, chicken and pig manure after 9 days were all minor than 20, which is indicative of a mature compost (i.e. lower than 25 according to the authors). The C/N ratio of various commercial other fertilizers varies from 6:1 to 36:1.

3.2.3.5 Contaminants (heavy metals, residual pesticides) BSF frass reported to have low concentration of heavy metals and pesticide residues due to the ability of BSFL to biologically accumulate heavy metals in their tissues and to degrade the pesticides with the help of enzymes (e.g. dehydrogenase) (Menino et al., 2021). Salomone et al. (2017) conducted an experiment where he measured the concentrations of toxic metals in the BSFL frass fed with food waste substrates and found that the concentration of toxic was below the limits stated in the Italian regulation for fertilizer and thus proved the ability of BSFL to reduce and accumulate various forms of heavy metals in the BSFL treatment process. One more study was carried out where large quantities of mercury have been added to the BSFL feedstock to be observed in a 13-day experiment and resulting in low mercury levels in the BSFL frass and were noted to be below the European Union's (EU's) threshold values of 0.7–10 mg Hg/kg (Attiogbe et al., 2019). Assessment of the heavy metal contents in BSFL frass showed 92–98% (0.0002–0.0008 mg/kg) removal of Arsenic, 99–100% (0.00029–0.00170 mg/kg) of Cadmium, and 80–90% (0.001–0.002 mg/kg) of Lead (Sarpong et al., 2019).

3.2.3.6 Maturity and stability Compost maturity refers to the degree of completeness of composting and absence of phytotoxic compounds and plant or animal pathogens that could negatively affect seed germination, plant growth and soil health (Bernal et al., 2017). The stability of compost can be identified when one that is no longer undergoing rapid decomposition and whose nutrients are tightly bonded; unstable compost, on the other hand, may either release nutrients into the soil owing to additional decomposition or tie up nitrogen from the soil (Insam et al., 2007). Within a short period of BSFL rapid composting (two weeks to a month), organic wastes fed by the BSFL may not be properly composted (Kawasaki et al., 2020; Song et al., 2021). The BSFL composting process must also stop when the larvae reach the prepupae stage, as a result, producing impartial compost, biologically unstable and immature compost (Insam et al., 2007; Setti et al., 2019). Therefore, it is preferred that this product should be given some sort of post-treatment (e.g. thermophilic composting), in order to stabilize it and making it suitable as a bio-fertilizer for cultivation (Alattar et al., 2016; Chirere et al., 2021; Song et al., 2021) and to promote the degradation of its organic matter and the mineralization of nutrients (Bernal et al., 2009; Chen et al., 2014). But, the stability of BSF frass is better than that of *S. gregaria*, *B. mori*, *S. icipe* and *T. molitor* and *G. krucki* (Beesigamukama et al., 2022). The formation of humic substances during composting of organic materials is one of the main indicators of compost stability (resistance to decomposition) and maturity (use for a determined purpose) (Zhou et al., 2014). These substances contribute to several soil fertility parameters by regulating soil acidity, improving the cation exchange capacity, increasing the water holding capacity, improving the uptake of nutrients and stimulating plant growth (Abbott et al., 2018; Canellas & Olivares, 2014; Conselvan et al., 2018; Olaetxea et al., 2018; Sutton & Sposito, 2005). According to studies (Barral & Paradelo,

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2011; Emino & Warman, 2004; Luo et al., 2018; Musyoka et al., 2019), the application of immature and unstable compost results in nutrient immobilisation and phytotoxicity, which inhibit seed germination and produce poor crop growth and yield. According to Liu et al. (2019), the feed substrate's high electrical conductivity and concentration of N-NH_4^+ may have contributed to the frass's lack of maturity. In contrast, Setti et al. (2019) found that the germination indexes were above 70%, indicating no sign of phytotoxicity. BSFL frass temperature range from 24 to 27 °C, if compared to the temperature of other compost (El-Haggar, 2007; Ho et al., 2022), which is suitable for microbial activity. The frass always has a lower C/N ratio than the feed substrate provided (Sarpong et al., 2019). The moisture content of BSFL frass varies from 10 to 65% depending upon substrate on which the BSF larvae feeds and the BSFL frass derived from fruit and vegetables is at 10% which is not suitable for agronomic purposes and may lead to hydrophobicity and be difficult to rewet (Basri et al., 2022).

4 Challenges and opportunities of products derived from black soldier fly treatment

4.1 Opportunities of products derived from black soldier fly

Global population growth, increasing wealth, and urbanization, particularly in Asia and Africa, create changes in global consumption patterns, lifestyles and food preferences, leading to an increase in animal protein demands (Smith & Barnes, 2015; Van Huis, 2013). This will affect the demand for livestock feed and inevitably place heavy pressure on already limited resources (Van Huis, 2013). Additionally, this will have an effect on the demand for animal feed and inevitably put a significant strain on already scarce resources (Van Huis, 2013). Protein shortages are caused by the rising demand, hence alternate sources of sustainable protein are required (Halloran et al., 2016; Van Huis et al., 2015). The cost of feed, including replacements like fishmeal and soybean meal, which accounts for 60–70% of production expenses, is one of the main restrictions (Vantomme et al., 2012). Protein sources, among other conventional feed streams, are subject to supply and import price fluctuations. According to recent estimates, the global feed market demand for poultry, pigs, cultured fish, and pets, respectively, is 464, 254, 35, and 23 million megagrams (Mg) (Alltech, 2016). Insect-based feeds are therefore anticipated to provide a significant contribution to the world's feed supply while minimising negative environmental effects (Dobermann et al., 2017; Makkar et al., 2014).

BSF are being used more and more sustainably to recycle organic waste into high-quality protein feed and organic fertiliser with no impact on the environment. Recent studies (Abro et al., 2020; Chia et al., 2019) demonstrate the technological and possible economic viability of BSF. According to Makkar et al. (2014), the dry BSF larvae contain about 42–49% crude proteins, 38% lipids, 20% crude fibre, 20% ash, and vitamins, all of which have been shown to enhance the production of pig, fish, and poultry (Kierończyk et al., 2020; Schiavone et al., 2017; Sypniewski et al., 2020). Due to its high nutrient content and potential for use as organic fertiliser, the BSF frass fertiliser is a by-product that is growing in popularity (Anyega et al., 2021; Bortolini et al., 2020; Gärttling et al., 2020; Lalander et al., 2015; Oonincx et al., 2015; Setti et al., 2019). Farmers who already raise BSF larvae for use as animal feed would benefit from the creation of frass fertiliser from BSF farming.

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Globally, BSFL business development yields an opportunity to initiate a zero-waste campus according to academics, helping to reduce food waste in cafeterias and colleges and other institutional settings (prisons, hospitals, and etc.). Segregated food waste from the community and oil palm wastes could be used as feed for BSFL. Production and insect milling processes in remote areas, support livelihood options in rural locations (Raman et al., 2022). BSFL produced at a large-scale can be marketed locally and commercial BSFL industries could expand and look to export BSFL products. Smallholder BSFL farmers could substitute costly animal or fish feed with low-cost BSFL as an alternative protein source for local poultry and aquaculture which reduce dependence on imported and high-cost animal feed (Raman et al., 2022).

4.1.1 Economical perspectives

Insects appear to be a component of a sustainable solution given the demand on natural resources and rising costs of conventional feed. Therefore, combining frass fertilizer from insects with animal feed offers greater economic advantages. This may enhance the lives and food security of smallholder farmers (Beesigamukama et al., 2022). Using BSFL frass as a value-added product has been added profitable for BSFL farming than using just the net income from BSFL animal feed. Compost-like qualities can be seen in BSFL frass (Bortolini et al., 2020). According to several studies (Attiogbe et al., 2019; Bortolini et al., 2020; Gao et al., 2019; Sarpong et al., 2019), the quick composting of organic waste by BSFL produced compacted BSFL frass with high macronutrients (NPK), micronutrients, and organic material contents that are immediately usable for agricultural application. In contrast to BSF farming alone, using BSFL frass fertiliser increased farmers' net income by 5–15 times, according to a study by Beesigamukama et al. (2020a). Rearing insects can provide livelihood diversification methods for many small-scale producers, thereby reducing vulnerability and supporting women's empowerment (FAO, 2014; Halloran et al., 2016; Crysantus, 2016). One megagram (Mg) of dried BSF larvae (USD 900) yields 10–34 Mg of BSFL frass fertiliser (USD 3000–$10,200) per megagram (Mg) of dried BSF larvae. Field trials were also used to assess the agronomic efficacy of BSFL frass fertilizer on maize crops.

Maize planted on BSFL frass fertilizer-treated plots had net revenue that was 29–44% more than maize grown on commercial organic fertilizer-treated plots. Furthermore, smallholder insect farmers who use BSFL frass fertilizer directly for maize growing will generate 30–232% more net revenue than farmers who buy identical BSFL frass fertilizer. The presence of chitin in BSFL frass also helps promote plant development and trigger plant defences (Surendra et al., 2020). Applying even a minimum amount of BSFL frass chitin to plants results in better growth, more flowers and seeds, and attracts more pollinators (Choi & Hassanzadeh, 2019). BSFL frass has a rich beneficial microbe (Gold et al., 2020), such as nitrifying and nitrogen-fixing bacteria that make nitrogen available for plant uptake (Choi & Hassanzadeh, 2019; Poveda et al., 2019). Nitrogen-fixing and nitrifying bacteria are crucial because fixed nitrogen is a limited nutrient in most ecosystems, and nitrate assimilation into plant roots makes soils more resilient to flood, drought, and land degradation. In addition, by enhancing nitrogen uptake, the high phosphorus concentration in the BSFL frass has aided in promoting nitrogen accumulation in plants since phosphorus is essential for energy transfer (Klammsteiner et al., 2020). BSFL frass can recapture nitrogen and phosphorus from the food chain for reuse as fertilizer, thus reducing the need for chemical fertilizers. Frass fertiliser can be used to obtain a lower optimum N rate (79 kg N/

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ha), which suggests that employing it would result in cheaper fertiliser costs and higher net profits, returns on investment, and gross profit margins (Beesigamukama et al., 2022).

4.1.2 Environmental perspectives

Unfortunately, there hasn't been much research done on how insect farming and using the frass as fertiliser affect the environment. Insect farming will gain more benefits because of BSF farming's social and environmental services. Therefore, additional research is needed to assess the economic viability and social-environmental benefits of BSF farming across various production systems in order to scale up insect-based feed and frass fertiliser sustainable and innovative technologies (Beesigamukama et al., 2022). Almost half of the global waste generation is food waste, which 37% of them go in landfills and 33% of them are disposed in open dumps area (Kaza et al., 2018). However, this food stream, which contains high concentrations of organic matter, macro- and micronutrients, if not properly disposed of, might constitute harm to the environment. Therefore, in ecological perspectives, BSFL frass production has contributed to the recycling of nutrients from food waste and has prevented the environment from becoming a concern owing to the emission of greenhouse gases and soil/water contamination with poisonous chemicals and nutrients from leachates (Lopes et al., 2022; Pang et al., 2020). Although the manufacture of insects depends on the environment, they generally have low land and water requirements and significantly reduced greenhouse gas (GHG) emissions (Halloran & Vantomme, 2013; Oonincx et al., 2010) as compared to other livestock production (Van Huis, 2013; Smith and Bernes, 2015; Oonincx et al., 2010) where, livestock was found to be responsible for 9% of CO_2, 35–40% of CH_4, 65% of N_2O, and 64% of NH_3 productions of all anthropogenic greenhouse gas emissions (Steinfeld, 2006). The production of insects has a much lower global water footprint than that of meat because they are cold-blooded, can obtain their moistness needs from food rather than necessarily needing drinking water, and can grow on organic waste (Mekonnen & Hoekstra, 2010; Miglietta et al., 2015). This helps conserve water.

4.2 Challenges of products derived from black soldier fly

4.2.1 Animal feed

Being a novel sector, production and sale of insects as feed faces several challenges, from legal to consumer acceptance and to industrialization and growth. Although the legal framework is changing and adapting to this new reality, consumers still have to prepare for it, and insect producers have a lot to learn from other livestock and industrial sectors (Alhujaili et al., 2023). According to Regulation EC Nr 1069/2009, insects used as food are regarded as Processed Animal Proteins (PAPs) in the EU (Smith & Barnes, 2015). Insects were no longer allowed to be used as animal feed as a result of Regulation EC Nr 999/2001's restriction on PAPs following the BSE crisis (EFSA Scientific Committee, 2015). Aquaculture species can now be fed non-ruminant PAPs according to an amendment to Regulation EC Nr 56/2013. Processed insect protein, however, is exempt from this requirement (EFSA Scientific Committee, 2015; Smith & Barnes, 2015). Additionally, on-farm killing of livestock, including insects, is prohibited by European legislation governing abattoir regulations. Since this law was not intended for insect killing, it hinders effective insect farming (Charlton et al., 2015;

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Smith & Barnes, 2015). In Australia, there are significant challenges to importing any kind of live insect, and companies must get approval to bring in insect-derived feed products. This will be a challenge for startups like AgriProtein as they look to enter the Aussie market with their branded MagMeal™ product (Nolet, 2017). A potential allergenic issue of the products derived from the BSF larvae is one more challenge to the farmers who are engaged in the rearing and processing (Halloran et al., 2016; Fitches, 2016). Therefore, for the large-scale insect farming sector to flourish globally, feasible production techniques must be devised (Fitches, 2016). The creation of a legal framework that must be upheld globally and across the board in order to achieve industry-wide standardisation is required. Since each government has different priorities (e.g., addressing the issue of food waste), it can be difficult to establish standardisation in terms of international trade (Vantomme et al., 2012). But dealing with this issue is essential (Vantomme et al., 2012). Leveraging BSFL as a sustainable food and feed source holds the promise of effectively managing waste, mitigating environmental pollution, and tackling the urgent challenge of food security in an environmentally conscious manner. Nonetheless, it is imperative to conduct additional research and foster innovation to guarantee the safety, quality, and economic feasibility of products derived from BSF for consumption by both animals and humans (Siddiqui et al., 2024).

High capital and operational costs to build and run the BSFL production, securing sufficient breeding stock, identifying a cost-effective BSFL production system, ensuring a constant and sufficient supply of organic waste of BSFL, high price of BSFL, challenges in obtaining constant BSFL supplies as an animal feed ingredient, lack of financial resources to conduct research, lack of knowledge on insect studies and skilled expertise to work in BSFL industries, lack of education of workers in food and beverage departments to segregate food waste in an industry with high staff turnover, high costs of a large supply of feed source for BSFL, challenges in ensuring constant BSFL nutrient quality as an animal feed ingredient (Raman et al., 2022). Dried BSF larvae nutritional value contains up to 50% protein, 35% fat, 6% calcium, 1.2% phosphorus, 1% magnesium, and 0.3% sodium but is greatly varies according to the source of substrate fed (Raman et al., 2022). Ministry of Agriculture and Food Industries of Malaysia mentioned that the current price of BSFL is similar to that of fishmeal, so despite its potential, BSFL's competitiveness (both in terms of price and nutritional value) needs improvement before it could replace fishmeal (Raman et al., 2022). Public perception of BSF as yucky insect and therefore public concerns about smell and hygiene for BSFL rearing area is of great importance. Convincing the government for potential use of BSFL as an animal feed ingredient is a difficult task. In order to prevent contamination and spoiling and to guarantee the safety of food and feed, safety considerations like adequate processing, handling, and storage are necessary. According to Schabel (2010), entomophagy has been linked to cases of botulism, parasitoses, and food poisoning, such as aflatoxins, and the zoonotic danger of insects as a whole need to be taken into consideration. While the BSF industry has successfully established a supply chain that revolves around utilizing waste and by-products to produce feedstuff through the larvae, there is an ongoing exploration of alternative and more challenging substrates for rearing the larvae. Simultaneously, there is a growing interest in uncovering novel applications of bioactive molecules derived from BSF beyond the traditional use in animal feed. This indicates a dynamic shift towards diversification and innovation within the BSF industry (Tettamanti & Bruno, 2024).

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4.2.2 Frass as fertilizer

Even though the BSFL treatment process may be sufficient for producing BSF larvae, the BSFL frass might be immature or unstable compost product because of its high moisture content. The characteristics of BSFL frass are influenced primarily by the properties of the substrate fed to BSFL (Surendra et al., 2020). Many organic waste substrates have a high moisture content (> 80%) (Lalander et al., 2020). Food waste from human consumption has a very high moisture content (about 85%), which is a favourable condition for BSFL production and could rapidly degrade food waste (Liu et al., 2019). However, the BSFL product from the food waste substrate has produce moist, grey, and clay-like texture. Although this wet BSFL frass does not represent mature compost characteristics, it also contains high ammonium concentration and has low porosity that could stunt plant growth when being applied as a soil amendment (Alattar et al., 2016). Kawasaki et al. (2020) also has conducted an in-depth investigation on the agriculture value of BSFL frass from food waste substrate. The result showed that the BSFL frass has a higher ammonium nitrogen concentration but lower nitrate–nitrogen content showing that BSFL frass in an anaerobic condition due to the present of high moisture content. Nitrate serves primarily as a source of nitrogen that ensures sufficient nutrition for plant development and soil microorganisms (USDA, 2014). A substrate with high moisture content could also reduce the efficiency of a BSFL treatment process and dry separation of BSF larvae and frass (Lalander et al., 2020). Cheng et al. (2017) reported that dry separation of the larvae from the frass is not possible when the moisture content of a food waste substrate exceeds 80%. However, the BSFL frass can be easily separated from the insect biomass using a 2.36 mm sieve when the moisture content of the food waste is 70–75%.

Reducing moisture content in the BSFL treatment process could result in slower BSFL growth. The BSFL also tend to crawl out of the treatment container as the high water content will lead to a lower temperature for BSFL to live at as they need a mesophilic temperature (~ 30) for optimum waste conversion (Pang et al., 2020). The wet separation process of BSFL frass is also cumbersome and time-consuming if the moisture content has not evaporated sufficiently during the BSFL composting (Cheng et al., 2017; Dortmans et al., 2017; Lalander et al., 2020). The BSFL frass must have 50% dry matter content for easy separation of the BSFL frass from the larvae (Cheng et al., 2017). The beneficial effect of BSFL frass with low moisture content is good for soil aeration and solubility; on the other hand, the BSFL frass with high moisture content could have inadequate oxygen supply for the plant (Klammsteiner et al., 2020). The adverse impact of BSFL frass leachates caused by the excess moisture content could also cause ammonia poisoning in the plant and stunt plant development if the BSFL frass is not appropriately applied (Zahn & Quilliam, 2017).

Bio-waste characteristics, including bio-waste and BSFL gut microbes, determine the properties of the BSFL frass (Gold et al., 2018). Even though BSFL reduces the heavy metals content in BSFL frass, the ecological risk posed by the BSFL producing BSFL frass containing pathogenic microorganisms is a grave concern (Surendra et al., 2020). The type of substrate determines the BSFL gut microbiome, and the BSFL excrement determines the microbiome in the BSFL frass (Klammsteiner et al., 2020). Some studies have identified the presence of potential foodborne pathogens, such as *Salmonella* spp. and *Bacillus cereus* (Kawasaki et al., 2020; Wynants et al., 2019) found a low presence of *Escherichia coli* in BSFL frass, but a disease-causing bacterium in plants,

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Xanthomonadaceae, is present in BSFL frass harvested from the treatment of food waste substrate. BSFL frass harvested from food waste (fruit/vegetable mix waste) serves as a reservoir for coliforms and gram-negative bacteria. The negative microbial community in BSFL frass could come from the microbial community of the initial substrate, and the inactivation of it by sterilization using high-energy electronic beam is rather unpromising result for BSFL rearing. Gold et al. (2020) reported that inactivating the microbial community in the initial food waste substrate reduced the efficiency of BSFL rearing, indicating that the microbial community of the initial food waste substrate is beneficial for substrate decomposition and/or BSFL growth. It is essential to conduct more research on the ability of common species of the BSFL intestinal microbiota (*Providencia*, *Dysgonomonas*, *Morganella*, and *Proteus*) due to their abundance in the BSFL frass produced from food waste substrate. Furthermore, both pre and post treatment could be crucial to increasing the revenue from BSFL frass as it may give significant impact to the maturity and stability of BSFL frass. The feed substrate has a large effect on the nutrients in the frass (Elissen et al., 2023). The nutrient availability of BSFFF is not optimum for plant growth, not for extended root growth which limits the potential of roots to explore nutrients from deeper soil layers (Gebremikael et al., 2022). The neutral to alkaline pH of the frass can lead to NH_3 emissions in case of higher NH_4 content, but high dry matter contents (Palma et al. (2020) and cannot be applied at high concentrations (Gärttling et al., 2020).

Depending on the geographical region, there may be obstacles in terms of regulations and the absence of established standards for utilizing insect-derived frass as a fertilizer (Poveda, 2021). The evolving use of insect frass in agriculture may outpace regulatory frameworks. Moreover, the nutrient composition of frass is subject to variations based on the diet of the larvae. If the larvae are not consistently and adequately nourished, the frass may not align with the specific requirements of certain crops (Kragt et al., 2023). Maintaining consistent quality poses a challenge, with factors like larval rearing conditions, feedstock, and processing methods all influencing frass quality. Implementing robust quality control measures is imperative for dependable and efficient fertilizer production (Siddiqui et al., 2024). The acceptance of insect-derived products in agriculture may encounter resistance, with consumers or farmers expressing skepticism, particularly if there is a lack of awareness regarding the benefits and safety of using insect frass as fertilizer (Poveda, 2021). Scaling up frass production to meet the demands of large-scale agriculture presents challenges, and the cost-effectiveness of mass production must be carefully evaluated to ensure viability for farmers (Beesigamukama et al., 2022). Proper storage conditions are essential for preserving frass quality, as inadequate storage may lead to a decline in its nutrient content over time. Establishing a reasonable shelf life is crucial for the practicality and usability of the product.

5 Global market of products derived from black soldier fly treatment

Many low-cost technologies, including CORS (Conversion of Organic Refuse by Saprophages), have been developed to raise BSFL as animal feed using biosolids like market wastes and human waste. These systems have the benefit of not requiring any additional facilities or structures (Klunder et al., 2012). It has been evaluated and determined that pilot and full-scale BSFL raising facilities are effective, however there are still technical issues with expanding the current BSFL systems. Commercial BSFL manufacturing as animal

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feed is a specialty of several businesses, but because their processes are confidential, academics cannot access them (Buiani, 2015). This is not necessarily a problem because new businesses will enter the production market and invest in R&D to better compete if the demand for BSFL increases. Innovation. After raising, BSFL or any other insects must be properly prepared, cleaned, processed, packaged, and stored throughout the process to be used as a safe animal food in markets that follow regulations (Wang & Shelomi, 2017).

Both Newton et al. (2005) and Kim et al. (2021), discovered that fresh organic biomass (1248 g) treated with BSF (1200 larvae) showed 60% reduction in organic matter and produce 1% biodiesel (15.6 g), 4% residual larvae (54.4 g), and 8% sugar (96.2 g). In addition, simultaneous improvement in BSFL body composition as rich in crude protein (42%) and crude fat (38%) also observed (Kim et al., 2021).

The impact of BSFL as a diets of channel catfish and tilapia was investigated by Bondari & Sheppard et al., in 1981. Consumers found the fish in this trial to be appetizing because there were no changes to its flavor or texture. The market's growing demand for sustainable food has compelled food companies to seek out novel protein-based alternatives that can substitute traditional muscle meat (Calderon et al., 2018).

5.1 Marketing perspectives of products derived from black soldier fly larvae: as animal feed and fertilizer

BSF can be sold in a variety of stages and forms. Marketable ingredients derived from the BSFL include whole BSF meal, the oil fraction, defatted protein meal, and various by-products (Mouithys-mickalad et al., 2020). The BSF possesses a dry matter content of approximately 95% and can be marketed in its entirety, either dried or processed into meal. In this approach, the protein composition and oil content of the BSF remain combined, as the product is not subjected to defatting. Consequently, the protein content of the product stands at around 40%, while its average dried oil content amounts to 30% (Amrul et al., 2022). It is possible to process and isolate the oil fraction from the BSFL's protein content. Protein levels in BSF protein meals can reach over 60% when they have been defatted (Jeon et al., 2011). Amino acids make up the protein. In its basic state, the BSFL's amino acid makeup is strikingly close to the protein content of soybean meal. When raised on organic waste streams, the BSF's precise amino acid content remains rather stable (Mwaniki et al., 2020). Upon processing the BSFL, it is possible to extract both the oil fraction and the protein fraction. The concentration of oil in the BSFL can vary significantly, ranging from 15 to 49%, depending on the substrates on which the BSFL were cultivated. In contrast, the protein component of the BSFL remains consistently stable (Bogevik et al., 2022). According to research, BSF fed with poultry dung achieves the lowest values while BSF fed with oil-rich meal achieves the best values. The BSFL's oil component is a complicated concoction of components. The fatty acid lauric acid and its esters make up the majority of the oil. One of the key ingredients in coconut oil is lauric acid (Ullah et al., 2022). The BSF contains additional valuable bioactive substances that remain in the larval mass after the mass's proteins and lipids have been removed. The precise oil and protein content of the BSFL determines the byproducts' specific percentage. Enzymes like ligninases and cellulases, which are utilized by the BSFL, among other things, to digest cellulose, are left over after proteins and oils have been removed from the BSFL (Rehman et al., 2023; Zhu et al., 2019). In addition, the BSF has chitins and peptides that fight germs (Van Huis & Gasco, 2023). Acetyl glucosamine sugar moieties are the main component of the polysaccharide known as chitins. The sugar chitosan can be removed via the chemical procedure known as

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alkaline deacetylation (Oteri et al., 2022). The BSF also includes antimicrobial peptides, which are useful as antibiotics, according to numerous studies (Sogari et al., 2019). BSF also includes additional by-products, such as residual compounds that are expelled after rearing. This primarily consists of feces, organic waste remnants, and BSF casts (Schmitt & de Vries, 2020).

5.1.1 BSF as animal feed

Currently, livestock are fed diets that contain soybean oil. An alternative is required since this type of oil has negative environmental effects. Some studies tested what would happen if BSF oil were substituted for soybean oil in the diet of broiler chickens (Van Huis & Gasco, 2023). When soybean oil was totally substituted with BSF oil in the feeds of broiler chickens, neither performance nor meat quality showed a discernible difference across the studies (Wang & Shelomi, 2017). One study also reported encouraging outcomes in terms of the amount of total cholesterol and liver fat in hens (Chen et al., 2022).

In an experiment involving the inclusion of BSF oils in the pig feed has been made. This trial demonstrated the usefulness of BSF oil for piglets in the nursery. It was shown that the nursery piglets responded favorably to the replacement of corn oil (another replacement for soybean oil) with BSF oil at a maximum proportion of 6% in their meals (Chen et al., 2022). The experiment had no unfavorable effects, and it even helped the pigs develop more quickly. In addition to feeding live BSFL to laying hens demonstrated that it will help to reduce the feather plucking associated problems and improve natural habitat. About 40% of the time spent by free-range hens is spent looking for and consuming insects. This aids in resolving problems with chicken welfare in present farms, such as feather plucking. The larvae are also a source of nutrition for hens, so it serves as more than just a stimulant for natural behavior. According to the results of the experiment, live BSFL can replace soybean meal if they are fed with some extra local protein. It had no detrimental effects on the performance or output of laying hens. Since there was less feather plucking among the chickens, it even improved the condition of the laying hens' feathers (Star et al., 2020).

In 2016, the Dutch feed manufacturer Coppens Diervoeding B.V. introduced its products and became the first company in the world to integrate insect oil into their chicken and pig feed (Van Huis & Gasco, 2023). Protix is an idea whereby laying hens from a certain poultry farmer are given live BSF, and since 2016, the eggs are sold to consumers under the brand name Oerei in shops in the Netherlands (Jackson, 2020). Grand View Research's estimates that the global poultry market had a total value of over 175 billion US dollars in 2018 and would continue to expand at a compound annual growth rate of 4.5% through 2025 (Global Industry Report, 2019–2025). The market for pig feed was valued at over 106 billion US dollars, with a compound annual growth rate of 3.5%, according to the same research firm. However, due to limited availability and legislation, numerous specialists at Protix claim that current market volumes containing insects are extremely small and inconsequential in comparison to the overall market. BSF oil is a viable substitute for soybean oil in the diets of broiler chickens and nursery pigs. Additionally, live BSFL supplemented with regional proteins can be used to replace soybean meal in the diets of laying hens. To enable a farmer to offer an innovative egg concept of chickens fed with live larvae in supermarkets, Protix is supplying the farmer with live larvae. The product BSF oil is now used in the production of pig and chicken feed; this is a market application for the product. Another current product market application is the use of live insects in the production of poultry feed (Hilkens & De Klerk, 2016).

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The primary market for insect production, which primarily consists of live BSF and mealworms, is the hobby pet food sector. On this market, people can buy fish bait, birds, reptiles, and amphibians (Lähteenmäki-Uutela et al., 2018). These critters feed on insects in the wild. Production firms that have been established for a while and primarily supply hobby-pet stores and zoos are the ones that focus on those markets. Although this market is seasonal, due to bird breeding season and reptile hibernation, there is less demand in the winter and the autumn (Lähteenmäki-Uutela et al., 2018). Dogs and cats make up the largest category of hobby pets globally; in 2018, there were over 470 million dogs and 370 million cats owned as pets globally (Okin, 2017).

In the USA, there is a sizable pet food market; the two main species, cats and dogs, are primarily carnivores. According to a study on the effects of cats and dogs on the environment, "if just one-quarter of the estimated 33% animal-derived energy in pet food was consumable by humans, it alone would support the animal-derived energy consumption of 26 million Americans" (assuming that the typical American diet consists of about 19% animal-derived foods). Therefore, the possibility for using insects in pet food is quite high (Higa et al., 2021).

BSF is a species deemed safe for incorporation in pet food. In Europe, BSFL, meal, and oil have received approval for utilization in pet food for several years. Authors are delighted to share that pet food manufacturers in the United States can now also embrace these innovative ingredients in the production of dog food and treats. This recent development occurred when the Association of American Feed Control Officials (AAFCO) decided to include adult dogs as one of the animals for which whole dried BSFL, BSF meal, and BSF oil are suitable. It is anticipated that the approval of BSF ingredients for use in cat food by AAFCO will transpire in 2022.

BSFL can also be used as pet food. Since meat is the primary source of protein for pet cats and dogs, the pet food industry is thought to be responsible for around 25% of the environmental effects of the meat industry. The number of pets globally is growing, according to research. The development of new protein sources is encouraged by the expanding rivalry because the pet food sector competes for the same resources as other food and feed industries (Kumcu & Woolverton, 2015; Okin, 2017). Insects can effectively replace (part of) the meat in pet food as a source of protein, according to Hilkens and De Klerk (2016). There have been three studies on the use of BSF in the diets of dogs or cats. The first trial demonstrated that feeding 2% whole BSF meal to beagle dogs enhanced their digestibility and had anti-inflammatory and anti-oxidative benefits (Zielińska et al., 2018). The results of a second experiment suggested that dog food utilizing whole BSF meal as a protein source was more easily digestible than dog food including typical proteins, such as meat (Higa et al., 2021). In the third trial with cats, whole BSF meal was used in place of the kitties' usual sources of protein. The majority of the cats in this experiment tolerated the BSF-containing chow, according to research, but the researchers still suggest more study. The partial replacement of traditional proteins in cat and dog food with BSF full BSF meal has shown positive outcomes in investigation. However, more investigation is required before any judgments can be made (Okin, 2017).

5.1.2 BSF frass

The market potential of BSF frass is substantial, thanks to its numerous benefits and the increasing demand for sustainable and organic agricultural products. As concerns about the environmental impact of conventional farming practices rise, the need for sustainable and

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organic alternatives is growing. BSF frass, being a natural and organic fertilizer, perfectly aligns with these principles, making it highly appealing to environmentally conscious consumers (Lopes et al., 2022).

One of the primary reasons for the high value placed on BSF frass is its nutrient-rich composition. Packed with essential nutrients like nitrogen, phosphorus, potassium, and micronutrients, it presents an attractive option for enhancing soil fertility and promoting robust plant growth (Beesigamukama et al., 2020a). By applying BSF frass to soil or plants, nutrient availability and uptake can be improved, leading to increased crop yield and improved produce quality (Berendsen et al., 2012). This benefit is particularly attractive to farmers seeking to optimize productivity and maximize the nutritional value of their harvests (Beesigamukama et al., 2021a).

Moreover, the remarkable ability of BSF larvae to consume and break down organic waste contributes to its market potential. This characteristic makes the larvae valuable in waste management systems, including food waste recycling and livestock manure management. Utilizing BSF frass helps convert waste into a valuable resource, effectively reducing the environmental impact associated with waste disposal (Beesigamukama et al., 2021a; Bernal et al., 2009). The versatility of BSF frass is another aspect that drives its market potential. It can be used across various agricultural applications, including field crops, vegetables, fruits, herbs, flowers, and even hydroponic systems. Its compatibility with different growing systems makes it adaptable to a wide range of market segments, enhancing its appeal to farmers and gardeners alike (Nyakeri et al., 2017; Wang & Shelomi, 2017).

While the use of BSF frass is not yet as widespread as other fertilizers, there is a growing awareness of its benefits and potential. As more research and information become available, along with increased adoption and success stories from early adopters, market awareness and demand for BSF frass are expected to expand. Overall, the market potential for BSF frass is promising, driven by the increasing demand for sustainable agriculture, organic products, and effective waste management solutions. As the market continues to evolve and more consumers and producers recognize its value, the demand for BSF frass is expected to grow.

5.2 Top global companies and countries leading the market of products derived from black soldier fly larvae: as animal feed and fertilizer

By 2033, the BSF market is anticipated to develop at a 30.5% CAGR (Compound annual growth rate) from 2022 to \$3.96 billion (Meticulous Market Report, 2022). This market is anticipated to expand in volume by 36.9% CAGR from 2022 to 8003.7 thousand tons by 2033 (Meticulous Market Report, 2022). The rising demand for meat worldwide is the key factor driving the expansion of the black soldier fly business. The market for black soldier flies is also being driven by the expanding aquaculture sector, rising soymeal prices, growing government support for the use of insect meal in livestock feed, rising investment by major BSF industry players, and rising demand from the animal feed sector for alternative proteins.

According to Meticulous Market Report (2022), top ten leading companies in BSF market are Agriprotein, Biofly Tech, Protix B.V., Entofeed Sdn Bhd, Nutrition Technologies Group, Enviro Flight Corporation, SFly Comgrof SAS, HexaFly, F4FSpA, and InnovaFeed. The primary market segments for black soldier flies are based on product, application, and region. According to product, the protein meal category is anticipated to hold the greatest market share for black soldier flies in 2022. The significant market share is mostly

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related to the rising demand for protein meals from producers of animal feed, the rising costs of soy and fish meals, and government backing and approval for the use of insect meal in animal feed. Additionally, the biofertilizers (frass) industry is anticipated to hold the greatest proportion of the overall black soldier fly market in terms of volume in 2022. The animal feed market is anticipated to experience rapid expansion over the course of the forecast period, depending on application. The rapid expansion of this industry is primarily related to increased demand for animal-derived goods and the ensuing rise in demand for animal feed high in protein, rising soy meal prices, and official approval of the use of BSF as an ingredient in animal feed. Additionally, there are numerous potentials for market expansion due to the increasing use of insects as a substitute source of protein in animal feed.

In terms of geography, Europe is projected to have the largest market share for BSF in 2022. This substantial market share can be attributed to the expanding aquaculture sector, increased interest in alternative protein sources for animal feed, and the upward trend in fish meal prices. Furthermore, throughout the projected period, Europe is expected to experience the highest (CAGR) in this field. Additionally, this region is anticipated to control the highest proportion of the worldwide black soldier fly market in terms of volume in 2022.

The global black soldier fly market is characterized by the presence of several key players, including Protix B.V. (Netherlands), Enterra Feed Corporation (Canada), InnovaFeed (France), EnviroFlight LLC (U.S.), Bioflytech (Spain), Entobel Holding PTE. Ltd. (Singapore), Entofood (Malaysia), Sfly (France), Hexafly (Ireland), F4F (Chile), Nutrition Technologies Group (Malaysia), nextProtein (France), and Protenga Pte Ltd (Singapore), among others, which are mentioned by Meticulous Research Market (2022). Some of the key leading companies in BSF market as animal feed and frass production are listed in Table 3.

6 Policy and regulations of products derived from black soldier fly treatment

In order to create more and larger batches of insects, it is necessary to be aware of potential techniques for stabilizing insects as intermediate or final goods, ideally with a cost–benefit analysis. Dehydration has so far drawn the most interest as a method of insect preservation in both industry and research. Chemical and microbiological breakdown processes are known to be slowed down or even stopped when water is removed from a product (Van Campenhout et al., 2021). The chemical and/or microbiological stability of dried edible insects during storage has been the subject of several investigations as for BSFL (Kamau et al., 2020; Larouche et al., 2019), for long horned grasshopper (Fombong et al., 2017), for yellow mealworm (Kröncke et al., 2018, 2019; Lenaerts et al., 2018), and for different cricket species (Bawa et al., 2020; Lee et al., 2020; Lucas-González et al., 2019; Vandeweyer et al., 2018).

Industrial-scale insect production primarily serves as a replacement for less environmentally friendly protein sources in feed. Currently, the most significant species raised for this purpose are the BSFL. The larvae must be transported and stored in a stable manner following production to prevent degradation. Both fermentation and vacuum packaging technology are viable stabilization options (Van Campenhout et al., 2021). The logistic chain includes stabilization, storage, and transportation in addition to the creation of

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Table 3 Leading companies involved providing BSFL as animal feed and its frass as fertilizer

Company Name	Continent	Country	Products	Product Packaging	Reference
BioFLY	South America	Colombia	BSF based larva flour, biofertilizer, dehydrated larvae, live BSFL	 	https://www.biofly.co/shop
Beyond Ag	Australia	Australia	Larvae, protein, chitin, Frass	 	https://www.bardee.com/protein
Beta Bugs Limited	Europe	UK	Larvae and Frass,		https://www.betabugs.uk/black-soldier-fly-products/
Chapul	North America	USA	Whole, Dried BSFL, Dark Popped BSFL, Light Popped BSFL, BSFL Meal, Digestate, BSFL oil, Frass	 	https://www.chapulfarms.com/products
Ecofly GmbH	Europe	Austria	BSF-protein, fertilizer, oil, whole dried BSFL, neonates		https://www.ecofly.at/en/products
FarmInsect GmbH	Europe	Germany	Larvae		https://farminsect.eu/produkte/#junglarven

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Table 3 (continued)

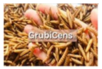
Company Name	Continent	Country	Products	Product Packaging	Reference
Insectta	Asia	Singapore	Larvae, Chitosan		https://www.insectta.com/our-insects
Inseco (Pty) Ltd	Africa	South Africa	Black Soldier Fly	 	https://inseco.co.za/our-products/#section-2-111
Little Fat Worm Biotechnology Company Ltd	Asia	China	Fish meal,		www.littlefatworm.com
Oberland Agriscience Inc	North America	Canada	Protein, Frass and Larvae	 	https://www.oberlandagriscience.ca/products
PROCENS	South America	Argentina	BSF based protein, oil, fertilizer and larvae	 	https://www.procens.org/productos/

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Table 3 (continued)

Company Name	Continent	Country	Products	Product Packaging	Reference
ProNuvo	North America	Costa Rica	Whole dried BSFL, Defatted BSFL protein powder, Natural BSFL insect oil, Organic BSFL frass		https://pronuvo.com/eng/our-products/
PT Magalarva Sayana Indonesia	Asia	Indonesia	Dried larvae, protein, oil, fertilizer, fresh larvae		https://magalarva.com/products
Protix	Europe	Netherlands	Pet feed, Oil, fertilizer		https://protix.eu/products_by_protix/#oerei
Sanergy	Africa	Kenya	BSF		https://www.regenorganics.co/products/
Vivotein	North America	USA	Whole dried BSFL, Live BSFL, Exotic feed, Frass		https://www.vivotein.com/products

larvae. A good preservation technique to pursue for the storage and transportation of BSFL is not thought to be vacuum packaging (Van Campenhout et al., 2021).

Van Campenhout et al. (2021), investigated the potential perseveration technology between vacuum packaging and fermentation for the BSFL. The vacuum packaging was applied to living, blanched and frozen larvae while fermentation pulverised blanched BSFL were used for the investigation. The vacuum packaged BSFL were stored for 6–10 days at various temperatures and gas composition, for the killed larvae-microbial counts while for the living larvae- survival rate recorded. In fermentation, the pulverised BSFL were fermented for one week at 35 °C and stored at 4 °C for two weeks, pH and microbial counts was observed and recorded. Author reported that fermentation allowed for the storage of pulverized larvae. However, certain factors to consider were the rapid decrease in pH and the presence of bacterial endospores. On the other hand, vacuum packaging did not offer any additional benefits compared to cooling alone. This conclusion applied to all types of larvae investigated. Thus, vacuum packaging is not considered a valuable preservation technique to pursue for the storage and transportation of BSFL (Van Campenhout et al., 2021).

Salomone et al. (2017), conducted measurements of toxic and essential metal concentrations in the BSFL frass that was fed with food waste substrates. The results revealed that the concentrations of both toxic and essential metals were below the limits specified in the Italian regulation for fertilizers. This indicates that BSFL frass has minimal amounts of heavy metals due to the capability of BSFL to effectively decrease and accumulate different forms of heavy metals during the treatment process (Basri et al., 2022).

In actuality, storage and transportation methods should be able to maximize the survival of living insects and (microbiological) quality of insects that have already been killed. The BSFL placed in pouches without a vacuum had the highest rate of survival (Rumpold & Schlüter, 2013). A lower storage temperature led to better survival, which indicated that the storage temperature was a significant influencing factor. Vacuum packaging has no beneficial effects on the microbiological quality of dead BSFL. The microbiological quality and dynamics of the gas composition in the package were significantly influenced by the initial microbiological quality following killing (which was better after blanching than merely freezing). Additionally, the insects' quality during storage was marginally improved by the lower temperature (Vandeweyer et al., 2021).

The "traditional" usage of insects as food is not usually connected to the regulatory framework governing the use of insects as feed, which varies greatly between nations globally. Table 4 gives a succinct overview of the laws that are now in effect in the different countries or union around the globe regarding the use of insects as feed.

Insects are a rising source of protein that is relevant to farmers, feed manufacturers, food producers, and food marketers worldwide. Due to antiquated food and feed restrictions regarding the use of insects, this industry's expansion is somewhat constrained. Since 2018, measures bringing insects under the purview of Regulation (EU) 2015/2283 on new foods have been in effect with regard to insects as food for human consumption. In accordance with this new Regulation, EFSA-approved marketing of insect feeding items is the only condition for their sale (Lähteenmäki-Uutela et al., 2018). Regulation (EU) No 2017/893 brought about one of the most significant modifications in 2017 with regard to insects used as animal feed. This legislation brought about amendments to Regulations (EC) No 999/2001 and (EU) No 142/2011, permitting the utilization of seven insect species as feed for aquaculture animals (Lähteenmäki-Uutela et al., 2021). These species include the house cricket (*Acheta domesticus*), black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), yellow mealworm (*Tenebrio molitor*), lesser mealworm

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Table 4 Laws or legislation for governing the insect (BSF) as food

Authority	Country	Remarks on Insects as feed	Reference
EFSA (European Food Safety Authority)	European union	Authorized insect fat in feed Authorization of processed animal proteins in aquaculture	European Commission (2017)
CFIA (Canadian Food Inspection Agency)	Canada	BSF products approved poultry use Raw materials for feeding require permission	Lähteenmäki-Uutela et al. (2018)
FDA (Federal Food and Drug Administration)	USA	For insects, an additional permission list or GRAS are required BSFL are a component of animal diet	Lähteenmäki-Uutela et al., (2021)
None	China	Not require	Lähteenmäki-Uutela et al., (2018)
Ministry of Agriculture, Food and Rural Affairs	North Korea	Strictly prohibited	Jo and Lee (2016)
Ministry of Agriculture, Food and Rural Affairs	South Korea	Not require	Han et al., (2017)

(*Alphitobius diaperinus*), banded cricket (*Gryllodes sigillatus*), and field cricket (*Gryllus assimilis*) (Lahteenmaki-Uutela et al., 2017).

Only one species of bug has been defined by the Association of American Feed Control Officials (AAFCO) as an animal food item for cattle feed. Aquaculture salmonids including salmon, trout, and char can be fed BSFL, including dried entire larvae (since 2016) and processed BSF meal (since 2018). The AAFCO's choice has been examined and authorized by the FDA (Belluco et al., 2017). It is worth noting that various feed-grade materials, such as pre-consumer food waste used as a substrate, by-products from food production like brewery grains, and other approved feed-grade materials, can all be utilized for the cultivation of black soldier fly larvae. Products made from black soldier flies have been approved for use in the feeding of broiler chickens, tilapia, salmonids, and other poultry such as chickens, turkey, ducks, and geese.

Another regulation category is pet foods. Mealworms, silkworm pupae, and black army fly larvae are all offered for sale as pet food in Canada (Arbour & Hoeung, 2016; Pisanello & Caruso, 2018). Brazilian scientists, farmers, and businesses are becoming more and more interested in using insects as food and feed, especially when it comes to feeding poultry black soldier fly meal instead of soybean meal. The use of insects as food and feed might one day be regulated internationally. The scientific community may approve the use of insects worldwide as food and feed (Allegretti et al., 2018). In the absence of a global food and feed administration organization, the global harmonization of substantive and procedural norms would prove advantageous for both business owners and authorities. The FAO/Who is Codex Alimentarius Commission is the setting for creating international feed and food standards (Lähteenmäki-Uutela et al., 2021).

Due to current ambiguous statutory limitations surrounding its usage as feed, the commercialization of BSFL is restricted. Under certain restrictions, the manufacture and trade of BSFL as feed is particularly permitted in the European Union, Australia, Canada, and the United States. It is interesting to note that while regulatory frameworks are now being developed, the majority of nations where entomophagy is a tradition lack particular restrictions regarding their usage as feed. Harmonizing the industrial upscaling of BSFL as animal feed requires an understanding of the legislative structure (Alagappan et al., 2022).

7 Life cycle assessment of products derived from black soldier fly treatment

It is necessary to enumerate the environmental effects connected with the entire life cycle of these processes in order to estimate the environmental profile of products derived from insects. An important method for analysing and assessing the environmental influence of industrial processes and insect-based products is life cycle assessment (LCA) (Spinelli et al., 2019). Technical advancements can aid a shift towards renewable energy, lessening the possibility for global warming. LCA demonstrate increased energy use in the generation of some insects, such as BSF and housefly larvae (van Zanten et al., 2015). According to Smith and Barnes (2015), "regions with year-round high temperatures, high density of concentrated animal operations, and presence of food processing industry facilities" are where the best insect-rearing facilities can be found. According to IPIFF, adding insects to conventional feed (such soybean or fishmeal) will ease the strain on the environment, protected areas, and the world's fish populations. The various parameters considered for LCA studies on BSF by different authors are discussed in Table 5. A comprehensive LCA offers

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Table 5 Parameters Considered for Life Cycle Assessment Studies on Black Soldier Fly, *H. illucens*

Life cycle assessment study	Parameters considered	Reference
BSFL as an alternative feed source and agro-waste disposal route	growth performance, feed conversion ratios and nutritional composition of diets, and harvested larvae and the remaining organic matter (frass), insect diets, harvest, transportation, insect production, BSF composting versus conventional agro-residue treatment, BSF versus soybean meal or fishmeal protein	Beyers et al. (2023)
Environmental impact scenarios of organic fraction municipal solid waste treatment with BSFL	material depletion, energy consumption, water use, and feedstock conversion, Equipment lifespan, Sub-product generation, Use of renewable energies, Energy consumption, Transport of the final products	Ferronato et al. (2023)
Greenhouse Gas Emissions	substrate quality, experimental design parameters, ambient conditions, sampling procedure, gas detection and measurement methods, account for GHG emission variations between studies, larvae age before the experiment, the larvae density, feed rate, feeding strategies such as continuous, intermittent, and bulk; and the housing chamber, volume, moisture content, sensory characteristics, chemical properties, rheology, porosity, and pre-treatment	Boakye-Yiadom et al. (2022)
Environmental performance of insect protein	insect diet(a] Vegetables with high economic value (mixes of grains, four, bran, vegetables and beer yeast) b]Vegetables with low economic value (distiller's dried grains with solubles, spent grains, cookie remains)	Modahl and Brekke (2022)
Food waste bio-conversion by black soldierfly larvae (*Hermetia illucens* L.)	Nitrogen emission during bioconversion, Substitution capability of mineral fertilizer, Energy consumption for drying, Substitution capability of protein feed, Energy consumption for separation, Nitrogen emitted during post-composting, acidification and terrestrial eutrophication	Guo et al. (2021)
Insect production and processing as a path to efficient and sustainable food waste treatment	insect meal, feed conversion ratio, larvae biomass, size, the weight and the composition of the larvae, temperature, relative humidity, photoperiod, rearing density,	Ites et al. (2020)
Chemical *v/s* Enzymatic-Assisted Extraction of Proteins from BSF Pre-pupae for the Preparation of Biomaterials for Potential Agricultural Use	Different phases of BSF rearing viz., adult mating, oviposition, egg hatching and larva, BSF biomolecule extraction and fractionation, extraction yield and bio-plastic preparation	Rosa et al. (2020)

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Table 5 (continued)

Life cycle assessment study	Parameters considered	Reference
Conversion of organic resources by BSFL: legislation, efficiency and environmental impact	Energy use, land Use, global warming potential, CO_2 emission	Bosch et al. (2019)
BSF bio-waste treatment—Assessment of global warming potential	Direct and indirect emission of CH_4, N_2O, system design, aeration rate, turning frequency, and/or feedstock used	Mertenat et al. (2019)
Sustainable use of *Hermetia illucens* insect biomass for feed and food	Water use, feed inputs, electricity and heat consumption, production yields from an industrial producer	Smetana et al. (2019)
Using black soldier flies (*Hermetia illucens*) to bio-convert waste from the livestock production chain	BSF breeding, BSF biomolecule fractionation, bio-plastic production	Spinelli et al. (2019)
Alternative Scenarios for Waste Treatment—Food Waste Production by the Mass-Retail Sector	Insect meal, electricity and diesel consumption, e direct emissions due to waste treatment, water consumption, leachate disposal, transport	Salomone et al. (2017)
Environmental impact of food waste bioconversion by *Hermetia illucens*	food-waste, output composed of dried larvae, protein content, lipid content	Salomone et al. (2017)
Biodegradable waste treatment systems through BSF	loss of nitrates through leaching and runoff, electricity production from biogas, phase of the digestate/compost produced, Ammonia volatilisation losses, Avoided emissions	Smetana et al. (2016)
Biodegradable waste treatment systems for sub-Saharan African cities	Anaerobic digestion, composting, downstream emission, system capacity and lifespan, CO_2 emission, transportation, energy utilized, electricity	Komakech et al. (2015)

a holistic perspective on the environmental impact of products derived from black soldier fly treatment. Analyzing each stage of the life cycle allows for the identification of potential environmental hotspots and informs sustainable practices in the production and utilization of these valuable insect-derived materials (Boakye-Yiadom et al., 2021).

7.1 The environmental benefits of products derived from BSF larvae: as animal feed and fertilizer

Because food systems are the main cause of environmental deterioration, recent publications have highlighted the need for diet change (FAO, 2021; Kim et al., 2020). In comparison to the base period average of 2018–2020, the output of meat worldwide is predicted to rise by 13% (44 Mt) over the next ten years, reaching 374 Mt by 2030 (OECD/FAO, 2021; p. 48). According to FAOSTAT 2021, the percentage of all agricultural emissions attributed to animals through intestinal fermentation and manure is 44% and 20%, respectively, in 2019. According to OECD/FAO (2021; p. 165), greenhouse gas productions from agriculture over the 2018–2020 period accounted for around 54% of all emissions (on CO_2 equivalence basis). Edible insects could be created to replace meat products and also be used as feed elements because they have a high protein content on the edge and a strong nutrient profile, making them a significant substitute to conventional cattle (Rumpold & Schlüter, 2013). Insects require very little land or energy to produce, and they can be produced quickly and all year round, unlike other feedstock such as soybeans. FAO endorsed insects for their sustainability benefits, saying, “Insects have a high food conversion rate, e.g. crickets require six times less feed than cattle, four times a lesser amount of than sheep, and twice less than pigs and broiler chickens to produce the same amount of protein.” And finally, insects can serve as a protein-rich substitute for the wild-caught fish that are often used as aquaculture inputs, rendering aquaculture a sustainable solution to overfishing (Slimen et al., 2023).

According to Celitron, 2021, cattle need 7.7 kg of feed to produce 1 kg of meat, sheep needs 6.3 kg, pork needs 3.6 kg, chicken needs 2.2 kg, and BSFL meat needs 1.5 kg. This leads to the inference that plant-based diets are preferable to animal products obtained from conventional cattle in terms of global water consumption as well as the increased demand for food brought on by an expanding worldwide population (Celitron, 2021). It would be exciting to compare insects’ water footprint with that of animal products as well as feed crops in terms of nutritional quality because they have a much higher feed conversion efficiency since they are cold-blooded, can derive their moisture demand from food and do not necessarily need drinking water, and can grow on organic waste (Van Huis, 2015). Nevertheless, it has to be considered, that the feed conversion efficiency of BSF is temperature-dependent (Chia et al., 2018). It may be inferred that temperature-controlled raising containers are required for insects to gain maximum mass in the shortest amount of time, use the least amount of food, and emit the fewest amount of emissions, which indicates greater energy consumption than for conventional livestock (Rumpold & Schlüter, 2013). In addition to the water used in the manufacture of food and feed, its effects on greenhouse gas emissions must be taken into account. Regarding livestock’s overall worldwide contribution to greenhouse gas emissions, it was discovered that cattle produced 9% of CO_2, 35–40% of CH4, 65% of N2O, and 64% of NH3 of all anthropogenetic greenhouse gas emissions (Rumpold & Schlüter, 2013). When comparing the environmental impact of lab-grown meat and mycoprotein-based analogues scored highest and insect-based and soy meal-based substitutes lowest (Smetana et al., 2015). But Onwezen et al. (2021) found that

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consumer acceptance is a challenge, because insect-based protein scored lowest, followed by cultured meat, while plant-based alternative proteins scored highest.

One of the ecological services that insects may offer is the decomposition of organic waste, and the insect diet and feed industry benefits from this ability (Aidoo et al., 2023). Dung burial is one ecological service offered by insects in nature (van Huis, 2022). Insects are frequently employed to break down agricultural and culinary waste when raising insects in large numbers for food. According to UNEP (2021), 931 million tonnes of food were wasted in 2019 (households 61%, food services 26%, and retail 13% of the total amount of food produced worldwide). BSF is one of the most effective bioconverters (Surendra et al., 2020). BSF can also create useful products like fertiliser, medicines, biofuels, lubricants, surfactants, cosmetics, and insect biomass (proteins, lipids) at the same time (Fowles & Nansen, 2020). House fly breeding was stopped by BSFL, which reduced manure by up to 50% (Edea et al., 2022). The larvae aerate and dry the waste as they process it, which inhibits bacterial development. Salmonella enterica and Escherichia coli 0157:H7 may be reduced by the larvae's alteration of the microbiota in manure (van Huis, 2013). BSF larvae decrease the nutrient concentration and the amount of manure residue, which results in a decrease in pollution that may be as much as 50–60% (Newton et al., 2005) and makes the environment less hospitable to house fly larvae. The sum of all these qualities results in less pollution and odours (Diener et al., 2011).

It is frequently emphasised as a benefit of BSF-based organics conversion that it is sustainable. With an emphasis on protein, several life-cycle assessments have looked into the sustainability elements of producing products produced from BSF (Suryati et al., 2023). BSF production was extremely efficient in terms of land use, but this scale of production had a higher impact on global warming than similar sources of protein for feed, like soy meal (Salomone et al., 2017; Smetana et al., 2016). BSF meat has less of an impact than food proteins like chicken meat in a number of areas, including acidification, land use, and the creation of greenhouse gases. The environmental influence of frass and what causes its variation may only be inferred indirectly from a conclusion about the effects of protein production, but it can still be useful for determining whether it might have a lower environmental impact than another source (Aragao et al., 2023). For instance, the production of BSF frass is anticipated to have a minor environmental effect than the production of chicken manure since BSF meat has a lower environmental influence than chicken meat across a wide variety of categories. Advanced estimations have been performed in two additional recent papers (Bosch et al., 2019; Smetana et al., 2019) on how the feed ingested by BSF affects the environmental consequence of their production. According to both studies, the environmental impact of the feed that BSF eats is a significant factor in influencing the environmental impact of the products made from BSF. Fortunately, BSF can eat a variety of environmentally friendly feed sources, even though some are currently prohibited by laws. The effects of feed sourcing on frass have an impact on the ecosystem as well. The reduction in our dependence on pesticides could have significant implications for biodiversity in the event that the bio stimulant capabilities of insect by-products in the frass are decisively proved to boost plant resilience to pests. Additionally, applying frass introduces organic matter that is absent from chemical fertilisers. The application of frass would also have the added benefit of increasing soil biodiversity in our agricultural ecosystems if frass research shows that the soil microbiome diversifies when it is treated. The effects of applying BSF frass on soil quality have not yet been thoroughly explored (Schmitt & de Vries, 2020).

BSFL has also been used in poultry feed as a partial replacement for maize or soy-based feeds, mainly because the species naturally colonizes and breaks down poultry manure and

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populations are often kept by poultry farms for the purpose of waste management and pollution reduction (Cullere et al., 2018). The environmental aids of insect mass production include low greenhouse gas emissions (van Huis, 2017), the small amount of land required to produce 1 kg of protein (Oonincx & de Boer, 2012), reduced land use due to lower feed-food competition (Makkar, 2018), and the ability to transform organic waste streams into high-value protein products (Meneguz et al., 2018). One innovative strategy and outstanding illustration of a sustainable circular economy is the usage of insects in the bioconversion of waste materials (Meneguz et al., 2018).

7.2 Life cycle assessment of black soldier fly farming: potency for animal feed and fertilizer

LCA is a decision-making tool that provides a comprehensive overview for evaluating a product's environmental performance during its entire life cycle such as climate change, GHG emission, acidification, and eutrophication (Larrey-lassalle et al., 2022). LCA offers a strong ecological tool in the movement toward sustainability and can support research and development, product and process development, labelling, marketing, and policy making. LCA communication can positively influence the purchase of eco-friendly products amid the growing consumer interest in environmental sustainability (Boakye-Yiadom et al., 2021; Cooper & Fava, 2006). The method complies with ISO 14040 and ISO 14044 requirements and entails gathering and assessing a product's inputs, outputs, and potential environmental effects across the course of its existence. Goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and result interpretation are the four interconnected elements that make up the technique (ISO 2006a, b). It is complex and iterative but flexible enough to allow life cycle experts to modify and model their product systems (Foppa Pedretti et al., 2021; Sultana et al., 2022). A systemized multi-season database of BSF production and processing from a pilot facility producing above average volumes is used to conduct an LCA for BSFL products. In order to define more sustainable solutions, these data are then analysed using attributional (definition of the best production and allocation amongst products) and consequential life cycle assessment methodologies (Smetana et al., 2019). Life cycle assessment containing the steps as Gaol and scope, Life cycle inventory. Life cycle impact assessment and Interpretation of black soldier fly farming for animal feed and fertilizer is depicted in Fig. 3.

7.2.1 Goal and scope

The production of insects is about to go from a pilot scale to an industrial scale. To show the potential of their production technique, producers at the pilot size have concentrated on stable, safe production (Smetana et al., 2019). The use of BSFL as animal feed, as well as its derived products, is limited by the type of feeding material for its rearing. EC No. 1069/2009 restricts the use of food waste as feeding material, especially when it contains or is derived from catering waste (European Commission, 2019). However, agri-food residues are permissible. Thus, studies with food waste as the substrate (50%) have focused solely on the environmental impact of organic waste bioconversion by the BSFL with bio-treated waste as the main product, though insect products could also be obtained. A BSFL value chain can generate several high-value products. Crude protein from the insect cake can be further processed to obtain bioplastic film (Nuvoli et al., 2021; Rosa et al., 2020; Setti et al., 2020). The bioplastics thus derived

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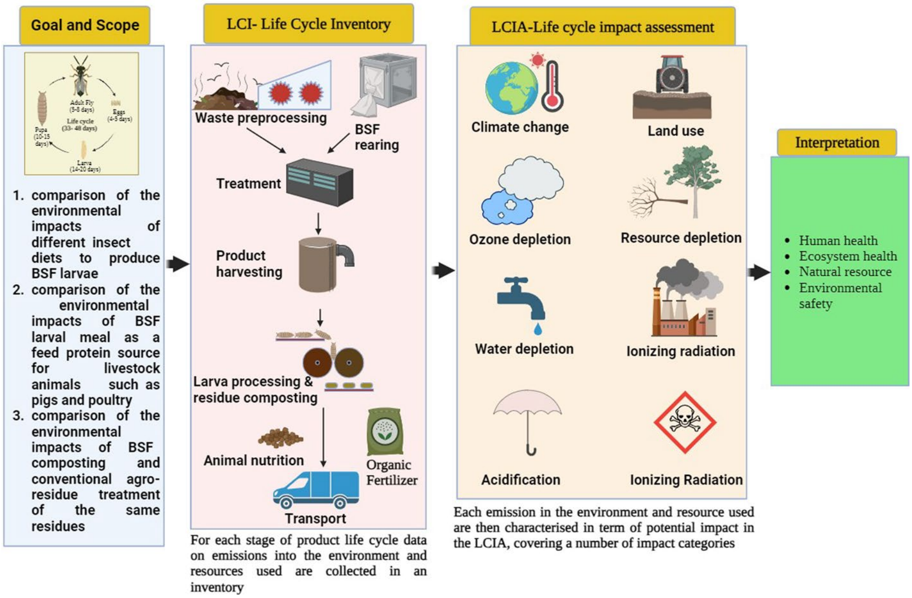

Fig. 3 Life cycle assessment of black soldier fly farming for animal feed and fertilizer

can be used in the agricultural sector (e.g. sheet mulching), aside from carrying out their primary function, act as a slow-release fertilizer, releasing nitrogen during their decomposition (Rosa et al., 2020; Spinelli et al., 2019). Chitin from insect meals can also be refined to produce an edible film, surgical thread, binders, and chitosan (Surendra et al., 2020). Refined fats/oil can also be re-refined into biodiesel and lubricating agents (Franco et al., 2021; Li et al., 2011; Wong et al., 2020). The residue, which is not assimilated by the larvae, is also useful for agronomic purposes, as it is high quality compost (Spinelli et al., 2019). According to Smetana et al. (2019), evaluations of these BSF-derived goods quantify their scope and identify the most promising avenues for the sector to realise the upcycling potential of insects. LCA has, however, been used on a few BSFL products. As a result, there is still a lot of room to lessen the impact that insects have on the ecosystem (Smetana et al., 2019).

The LCA take a multi-dimensional approach in order to understand the various environmental implications of insect production (Beyers et al., 2023). Any life cycle assessment system's typical objective is to evaluate the factors that affect the environmental impacts of intermediate insect-based products (useful for feed, food, and fertiliser) and to offer recommendations on how the industry should proceed in order to maximise the use of insects while minimising their environmental impact, with a focus on the potential use of unused biomass from the food and feed industries (Smetana et al., 2019). The study typically has two sections. The historical production data from a pilot plant are first subjected to LCA assessments. These are carried out to comprehend the environmental dynamics of the production of BSF. To identify areas for improvement to reduce the environmental impact, sensitivity analysis of industrial advancement is performed in the second stage (Smetana et al., 2019). The goals for LCA studies are discussed in Table 6 studied under various LCA model by different researchers.

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Table 6 Overview of the goals of Life Cycle Assessment studies on *Hermetia illucens*

Country	LCA Model	The goal of the study	Reference
Denmark	Attributional	To understand the various environmental implications of insect production	Beyers et al. (2023)
Italy	Attributional	Identify the most relevant EII (Environmental impact indicators) of the whole process, highlight the process that predominantly affects the OFMSW (Organic fraction municipal solid waste) treatment by BSFL, and to define the main parameters that mostly change the results	Ferronato et al. (2023)
Netherlands	Attributional	To transform existing knowledge on insect proteins into LCAs, to facilitate a comparison with more conventional protein sources	Modahl and Brekke (2022)
China	Attributional	Revealing the environmental impact of a BSFL bioconversion plant	Guo et al. (2021)
Germany	Attributional	Determining the environmental impact of using insects to treat food waste in a modular system	Ites et al. (2020)
Italy	Attributional	LCA of BSF protein-derived bio-plastic and comparison of two protein extraction protocols	Rosa et al. (2020)
Switzerland	Attributional	LCA to compare the global warming potential (GWP) of BSF biowaste treatment and composting	Mertenat et al. (2019)
Germany	Attributional	LCA on production stages of insect-based products and its comparison to benchmarks	Smetana et al. (2019)
	Consequential	Identifying the environmental consequences of production and consumption choices toward insect-based feed and food	
Italy	Attributional	LCA on laboratory-scale production of innovative bio-plastics made from biopolymers derived from BSF proteins	Spinelli et al. (2019)
Netherlands	Attributional	LCA on the production of fresh BSF larvae reared on different organic biomass resources	Bosch et al. (2019)
Italy	Attributional	LCA on the mass-rearing and food waste bioconversion by BSFL in a pilot plant	Salomone et al. (2017)
Germany	Attributional	LCA of insect production and processing at an industrial scale	Smetana et al. (2016)
Uganda	Attributional	Comparing the environmental impacts of different biowaste treatment technologies	Komakech et al. (2015)

7.2.2 Life cycle inventory

The harmonisation of LCA methodology is essential for a fair and more accurate comparison of environmental sustainability between different products (Santero & Hendry, 2016). Therefore, Life cycle inventory (LCI) analysis involves creating an inventory of flows from and to nature for a product system**.** Inventory flows include inputs of water, energy and raw materials, and releases to air, land and water. Using information on inputs and outputs, a flow model of the technical system is built in order to generate the inventory. The accuracy and reliability of LCA results can be strongly impacted by the quality of the data and critical assumptions, which might result in incorrect conclusions (Zargar et al., 2022). Sometimes, the unavailability of the correct inventory data can hinder the inclusion of key inputs or emissions in inventory modelling. Conducting an LCA for BSFL products requires data on direct GHG emissions from the bioconversion phase. Most LCA studies on BSFL struggle to consider these emissions as part of their inventory modelling, mainly due to the unavailability of reliable background data (Boakye-Yiadom et al., 2022). Some studies did not include it under the assumption that it was negligible (Salomone et al., 2017). Others also included emission data for other insects (Smetana et al., 2019), which is not ideal. Mertenat et al. (2019) analysed the systems viz., BSF rearing, waste-processing, waste treatment, product harvesting, larvae processing, residue composting, cleaning, avoided emissions, fishmeal production, transport and composting.

Results show that the overall Global Warming Potential (GWP) for BSF treatment mainly depends on the type of residue post-processing and the electricity consumption and energy source used (Mertenat et al., 2019). Non-agro residues, insect production, energy and materials consumption and remaining emissions are stages included in conventional agro-residue treatments and insect production (Beyers et al., 2023) indicates that the balance between insect production and alternative protein sources depends greatly on the insect feed used and the source of energy for heating during insect production. Salomone et al. (2017) considered parameters viz., transport of input materials, egg and larvae production, substratum production and compost & dried larvae production for LCA analysis during LCA of BSF for studying the environmental impact of food waste bioconversion by insects.

7.2.3 Life cycle impact assessment

All of the many inputs entered during the LCI phase are given environmental burdens by the LCIA. The environmental impacts are first categorised into the proper impact categories and referred to an intermediate position along the cause-effect chain, resulting in the so-called midpoint results. Thereafter, they are grouped into damage categories and allocated at the location where the environmental effect occurs (i.e., the end point results) (Rosa et al., 2020). The Environmental Footprint 3.0 technique was chosen for the impact assessment because it was established for Europe and provides for simple normalisation and weighting (Fazio et al., 2018). The broad suggestions of the Product Environmental Footprint (PEF) Method (Annex I of PEF) are also permitted to the greatest extent possible since no Product Environmental Footprint Category Rule has been defined for insect production (European union website). To calculate the environmental impact, the LCIA data were modelled using the IMPACT 2002+approach (Jolliet et al., 2003). Compared to other techniques, this impact assessment method contains more compounds and covers

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more impact categories. It offers a thorough assessment of the environmental performance because it is middle and endpoint orientated. However, in order to describe the system under consideration in a more representative manner, the following additions and modifications were made: modification to land use (different types of land transformations are considered), mineral extraction categories (additional resources are added), and radioactive waste (radioactive waste and its occupied volume are evaluated) (Spinelli et al., 2019). The midpoint and endpoint values are used to calculate the LCIA results. We only report the endpoint outcomes, though, in order to keep this short. These effects are typically depicted as having an effect on ecosystem quality, climate change, and resource depletion. The results of LCI can be used to evaluate the life cycle impact, including its effects on the environment. According to the associated inventory, five impact categories were selected: GWP, terrestrial eutrophication, marine eutrophication, acidification and particulate matter. The International Reference Life Cycle Data System (ILCD) Handbook (Laurent et al., 2014) will be used to determine the characteristics of the corresponding inventories in the selected impact categories. To evaluate how the systems under consideration would affect the environment, SimaPro 8 software (Prè Consultant, 2010) is employed.

7.2.4 Interpretation

According to Cao (2017), life cycle interpretation is a systematic process aimed at identifying, quantifying, verifying, and assessing data obtained from both the life cycle inventory and life cycle impact assessment. The interpretation phase involves condensing the results of the inventory study and impact assessment, ultimately leading to the generation of findings and recommendations. As defined by ISO 14040:2006, this phase encompasses the identification of major concerns based on the outcomes of the LCI and LCIA stages in a LCA. It involves estimating the study's completeness, sensitivity, and consistency through thorough checks, and addressing findings, limitations, and recommendations.

A key objective of life cycle interpretation, in accordance with Cao (2017), is to determine the level of confidence in the final conclusions and communicate them in a fair, thorough, and accurate manner. This emphasizes the importance of transparent and clear communication of the assessment results.

Additionally, in line with the advice from Clavreul et al. (2012), a sensitivity analysis was conducted. This analysis aimed to identify which factors had a disproportionate impact on the final outcomes of the life cycle assessment. Sensitivity analysis is crucial for understanding the robustness of the results and recognizing key variables that significantly influence the overall findings. By considering the advice of Clavreul et al. (2012), the interpretation phase becomes a more robust and comprehensive process, ensuring that the LCA outcomes are reliable and well-informed.

8 Conclusion

This review aimed to assess the viability of utilizing products derived from black soldier fly (BSF) for animal feeds and fertilizers. In the realm of animal feeds, BSF emerges as a sustainable protein source with applications in diverse food products for consumers. Particularly noteworthy is the suitability of BSF protein meal as a substitute for soybean meal in the diets of laying hens, weaning and growing pigs, finishing pigs, and fish. Incorporating BSF and BSFL into finishing pig diets even enhances meat and carcass quality. Despite

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these benefits, current regulations hinder the introduction of these products into the western livestock feed market. Additionally, by-products of BSF, such as antimicrobial peptides, show potential for serving as novel antimicrobial medicines for animals and humans. Chitin, another BSF by-product, exhibits immunological effects on human lung diseases and holds promise for medical applications.

In the domain of organic fertilizers, BSF larvae frass emerges as a valuable option for sustainable cultivation globally. However, further investigation is needed regarding the potential of frass obtained from composting biodegradable wastes using BSF larvae. The composition of frass varies considerably, with nutrient concentrations like P, K, and micronutrients being heavily dependent on the feed substrate. As frass may not possess the optimal nutrient composition, particularly being P-dominated, supplementing it with another nutrient input, specifically N-dominated, could create a more balanced fertilizer. Future studies should explore nutrient supplementation for frass-based fertilizers to meet the specific needs of different crops. Additionally, the role of bio-stimulants, plant growth-promoting rhizobacteria, and fungi in BSFL frass requires further exploration, offering significant potential for advancing sustainable cultivation practices globally. A comprehensive approach connecting different process steps with various aspects of interest is crucial for fully understanding the potential of BSF-derived products in animal feeds and waste-derived fertilizers.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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